

THE UNIVERSE

THE STORY SO FAR

—●—

YOUR DEFINITIVE GUIDE TO THE
WONDERS OF THE COSMOS

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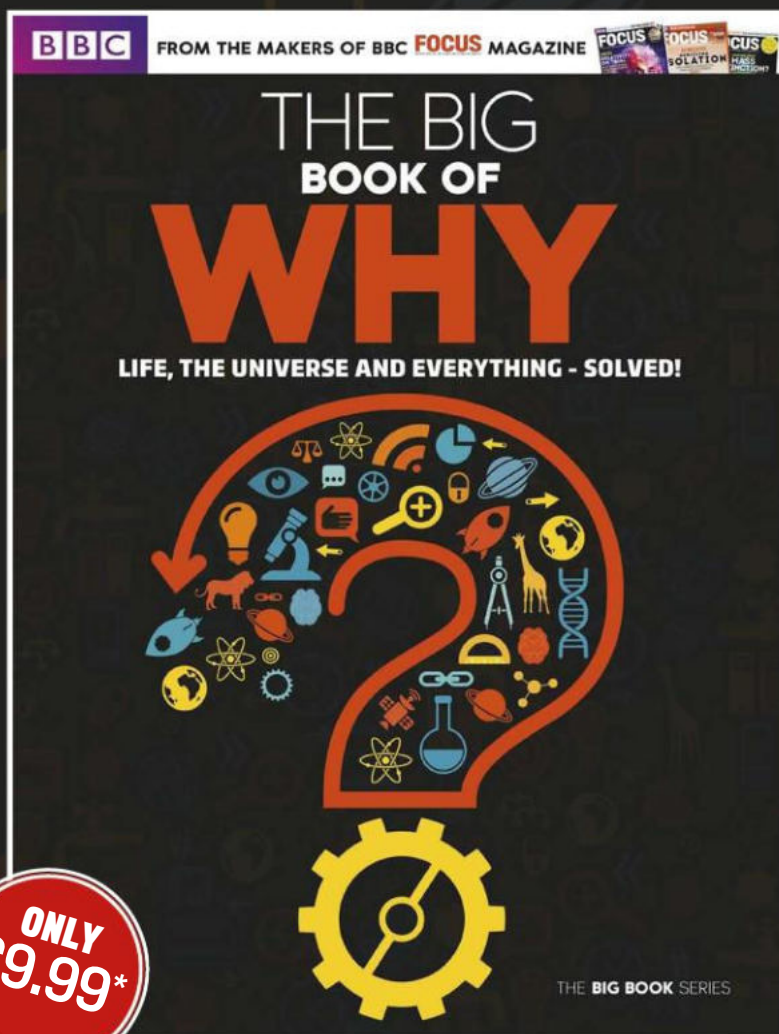
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WELCOME...



Space is full of surprises, and it seems like not a month goes by without scientists revealing another thrilling discovery.

Who could forget the awe-inspiring images of Pluto, sent back by the New Horizons mission, or the fascinating news that Mars may have water? We are only just starting to scratch the surface of understanding our own Solar System, so who knows what could be waiting in the far-reaching arms of the Milky Way and beyond?

In *The Universe: The Story So Far*, brought to you by *BBC Focus*, we have gone back through 13.8 billion years of history to reveal everything we know about the cosmos to date. We take a look at past and current missions of ESA and NASA, investigate mysterious worlds outside our Solar System, uncover the moons that could contain life, decipher the mind-bending theory of dark matter, and much more. We've even compiled some handy fact files about our Solar System, so you can super-charge your knowledge about our planet's closest neighbours.

We all enjoy staring up at a clear night sky and, with a copy of *The Universe: The Story So Far* in your hands, you can enjoy a greater understanding of what's really out there. But are there any little green men? Well, you'll have to turn to page 96 to find out...

Enjoy!

Alice Lipscombe-Southwell, Managing Editor



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While every attempt has been made to ensure that the content of *The Universe: The Story So Far* was as accurate as possible at time of press, we acknowledge that some information contained herein may have since become out of date. Also, the content of certain sections is occasionally subject to interpretation; in these cases, we have favoured the most respected source.

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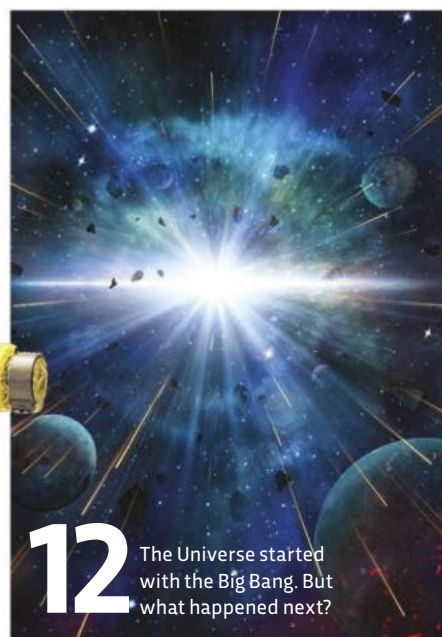
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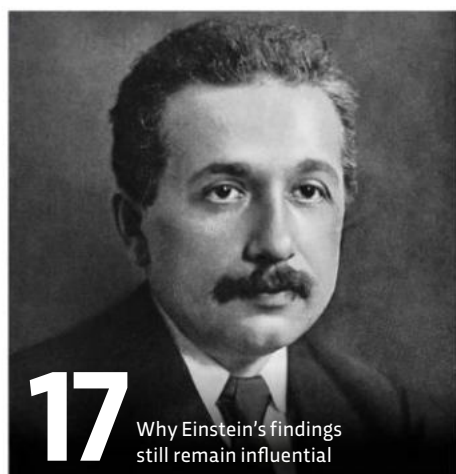
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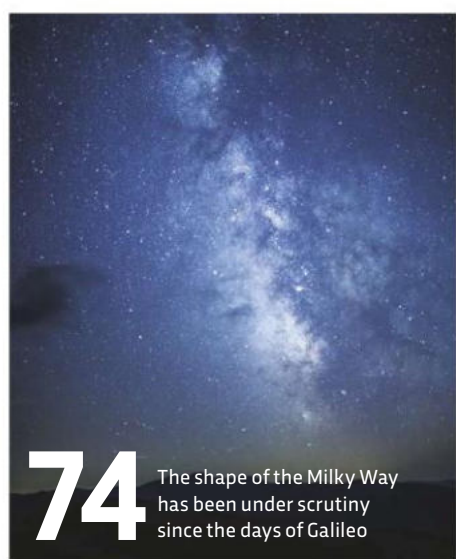
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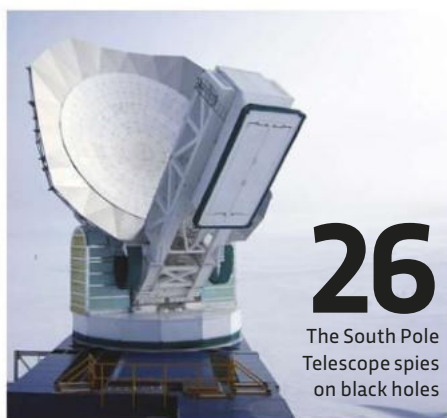
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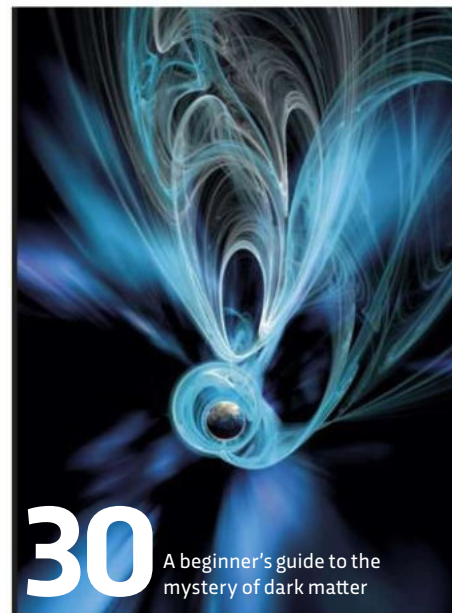
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THE UNIVERSE STARTED WITH A BIG BANG

Finding proof that our Universe expanded from a single point was a long and drawn-out process. Ultimately, though, says JOHN GRIBBIN, it became one of humanity's greatest discoveries

The idea that the Universe was born in a hot, dense state – the Big Bang, as the British astronomer Fred Hoyle dubbed it – is one of the most important scientific concepts. But the idea itself is less than

100 years old, and it wasn't until 1965 that proof emerged there really was a Big Bang. Solid evidence was found in the form of the so-called Cosmic Microwave Background Radiation. By then, though, there was already plenty of circumstantial evidence.

With hindsight, we can see the genesis of the Big Bang idea in a paper published by the Russian mathematician Alexander Friedmann in 1922. Friedmann realised that the equations of Albert Einstein's General Theory of Relativity, which describe the behaviour of space, time and matter, allowed for the possible existence of different kinds of universe. Some started out small and expanded as time passed. Some started large and shrank as time passed. Some grew from a tiny point out to a certain size then collapsed back into a point. At the time, there was no firm evidence that any of these mathematical models matched the Universe in which we live.

This didn't stop Friedmann speculating. In 1923, he wrote: "It is useless, due to the lack of reliable astronomical data, to cite any numbers that describe the life of our Universe. Yet if we compute, for the sake of curiosity, the time when the Universe was created from a point to its present state, ie, time that has passed from the 'creation of the world,' then we get a number equal to tens of billions of usual years." This is pretty close to the accepted modern value of 13.8 billion years, but nobody took any notice at the time.

Friedmann didn't know there was already astronomical data that supported his idea. At the Lowell Observatory in Arizona, Vesto Melvin Slipher had been studying the light from objects then known as nebulae – spiral 'clouds' of material. There was a debate about whether these were clouds of gas within the Milky Way, perhaps sites of star formation, or much larger objects far beyond the Milky Way – galaxies in their own right.

To his surprise, Slipher found the light from these spiral nebulae is 'redshifted', by a large amount. The naive explanation for this was that the objects are moving rapidly away from us, and the redshifts are caused by the Doppler effect. This suggested that they were indeed beyond the Milky Way. But there is another possibility. In the expanding Universe models discovered by Friedmann (but which Slipher knew nothing of), a similar redshift effect is produced by the stretching of space as time passes.

MEASURING DISTANCE

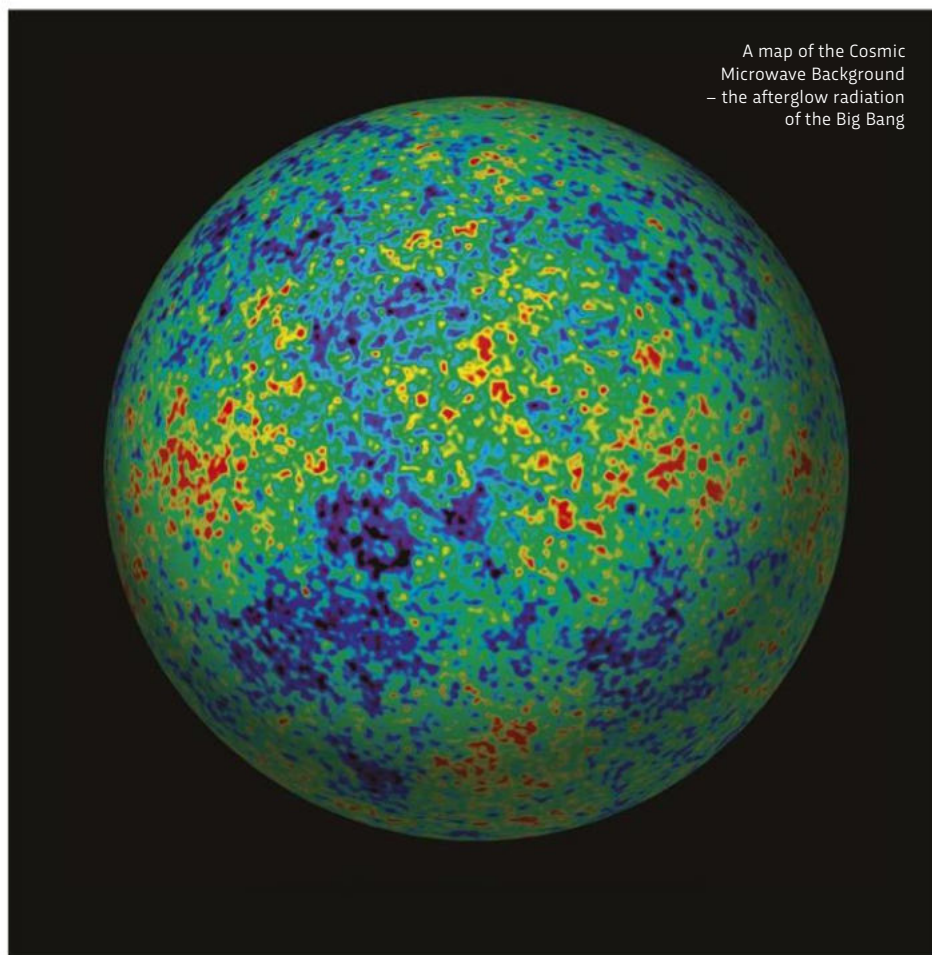
The debate about the nature of the spiral nebulae was resolved in 1924. Edwin Hubble, working at the then-new 100-inch telescope at Mount Wilson in California, measured the distance to the Andromeda Nebula (or galaxy) by studying variable stars known as Cepheids within the 'nebula'. This established that the spirals were indeed galaxies far out into the Universe. The time was ripe for someone to put redshifts and distances together, adding in the equations of the General Theory of Relativity to provide a description of our Universe.

That someone was Georges Lemaître, a Belgian mathematician/astronomer who had met both Slipher and Hubble, but who was completely unaware of Friedmann's work. So when he independently discovered the same solutions to Einstein's equations that Friedmann had found, his interpretation of the equations was based on observations of the real Universe. Putting everything together, he discovered that the redshift of a galaxy depends on its distance from us – its 'velocity' is proportional to its distance. But he was aware that this is not a Doppler effect. As he put it in a 1927 paper, the redshifts are "a cosmical effect of the expansion of the Universe". But that paper was published in an obscure Belgian journal and nobody noticed it – even though he sent a copy to the leading British astronomer of the day, Arthur Eddington.

Meanwhile, Hubble had been busy. He recruited a more junior astronomer (but the best observer in the world), Milton Humason, to measure redshifts of galaxies, while Hubble measured distances by a variety of techniques. In 1929, Hubble and Humason published a paper based on a study of 24 galaxies, 20 of which



A map of the Cosmic Microwave Background – the afterglow radiation of the Big Bang



IN A NUTSHELL

How the Universe began was one of the biggest questions facing science. Over the course of the 20th Century, a series of astronomical observations and fortuitous physics experiments finally verified the Big Bang theory.

TIMELINE

It could be the biggest question of all: how did the Universe begin? It took decades of discovery to answer...



Edwin Hubble discovers that the distance of a galaxy from us is directly proportional to the velocity implied by its redshift. Georges Lemaître had published this in 1927, but nobody had noticed.

1929

1931

Lemaître writes in *Nature*: "We could conceive the beginning of the Universe in the form of a unique atom, the atomic weight of which is the total mass of the Universe."



1964



Ralph Alpher (left) and Robert Herman calculate that the leftover radiation from the primeval fireball should still fill the Universe today, with a temperature of about 5,000°C. This was also published in *Nature*.

1948

Arno Penzias and Robert Wilson discover a weak hiss of radio noise coming from all directions in space. The following year this is explained as the leftover radiation from the Big Bang.

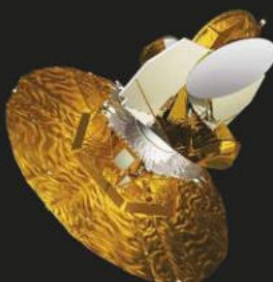


1989

Launch of the Cosmic Background Explorer satellite (COBE), which detected tiny irregularities (ripples) in the background radiation, confirming the accuracy of the Big Bang model.

2001

Launch of the Wilkinson Microwave Anisotropy Probe (WMAP), which makes precision measurements of the background radiation, pinning the age of the Universe down as 13.8 billion years.



→ had redshifts measured by Slipher, and four with 'new' redshifts obtained by Humason.

This was enough for Hubble to publish the now-famous discovery of the redshift-distance relationship. It showed that the distance of a galaxy from us is directly proportional to the velocity implied by its redshift. This – exactly what Lemaître had published two years earlier – became known as 'Hubble's Law'. The value of the Hubble constant in the Hubble and Humason paper was 500km/s per Mpc, suspiciously close to Lemaître's value. There was no mention in that paper, though, of either Slipher or Lemaître. Hubble, a notoriously vain and unpleasant self-publicist, did everything he could to take all the credit and glory – and, to a large extent, he succeeded.

This time, the news spread like wildfire. Lemaître, understandably miffed, wrote to Eddington reminding him of the 1927 paper, and Eddington did everything he could to spread the news of Lemaître's priority, including getting a translation of the paper published in English. Lemaître eventually got the credit he deserved, but it was Hubble who got the law named after him.

Lemaître, though, wasn't finished. Hubble was only interested in using redshifts to measure distances and never tried to fit them to any cosmological model. Most relativists simply regarded the equations as something to play with, of no relevance to the real world. Lemaître, though, took them at face value and used them to attempt a description of how the Universe began. In 1931, he speculated that the Universe might have begun violently (in 'fireworks') in a very dense state, which expanded dramatically to become the world as we see it today. He developed these ideas in a book published in 1946, referring to the origin of the Universe either as the 'primeval atom' or the 'cosmic egg'. This inspired the Russian-born American George Gamow to take up the idea and develop it further, with the aid of his colleagues Ralph Alpher and Robert Herman.

Ralph Alpher realised that the heat from Lemaître's 'fireworks' should have filled the Universe with electromagnetic radiation, which would still exist today in the form of cold radio waves. In 1948, he published a paper in the journal *Nature* concluding that 'the temperature in the Universe at the present time is found to be about 5 Kelvin [-268°C].' Gamow promoted the idea for a time (and now often incorrectly gets the credit for it), but in those days nobody thought that such cosmic background radiation could be detected, and the idea was soon forgotten.

The Universe was born from a single point in time and space, a discovery made possible by identifying the radiation from the Big Bang itself



But there was a problem with the Big Bang idea, as it was being called by the 1950s. The speed with which galaxies are moving apart today tells us how long it has been since they were all squeezed together in Lemaître's cosmic egg. This 'age of the Universe' is related to Hubble's constant – the bigger the constant, the faster the galaxies are separating and the younger the Universe. For a value of 500km/s per Mpc, the Universe would only be about a billion years old – far younger than the known ages of the Sun and stars. This encouraged the rival Steady State model of the Universe, which says that the Universe has always existed and always expands, but that new atoms pop into existence as space stretches to make new galaxies which fill the gaps.

BELATED ACCEPTANCE

The Big Bang idea gradually became more respectable as better telescopes and improved observations showed that the Hubble constant is much smaller than Lemaître and Hubble had estimated – less than 100km/s per Mpc. Then came the decisive moment.

In 1964, Arno Penzias and Robert Wilson were adapting a radio telescope built to test satellite communications for radio astronomy. The telescope, at Crawford Hill in New Jersey, belonged to the Bell telephone company. Before it could be

used for astronomy, it had to be calibrated. Penzias and Wilson found that it was plagued by what seemed to be interference; a weak hiss of radio noise showed up in the instruments no matter which part of the sky they pointed the telescope to. They were utterly baffled. Then, in December 1964, Penzias happened to mention the problem to another radio astronomer, Bernard Burke, who said that he knew of a team at Princeton University who might be able to shed some light on the problem.

That team was headed by Jim Peebles and Robert Dicke, with two junior colleagues, Peter Roll and David Wilkinson. Dicke had independently come up with the same idea as Ralph Alpher, but had gone one step further by initiating a project to build a telescope to look for the predicted radiation. The telescope was nearly complete when Penzias and Wilson got in touch.

The two teams put their heads together, quickly establishing that what Penzias and Wilson had found could indeed be the 'echo' of the Big Bang. They produced a pair of papers for the *Astrophysical Journal*. Dicke, Peebles, Roll and Wilkinson came first, setting out the theory of leftover radiation from a hot early Universe. That paper was then followed by Penzias and Wilson with 'A Measurement of Excess Antenna Temperature at 4,080 Mc/s', making no mention of the significance of the discovery except for the sentence:

UNDERSTANDING THE BIG BANG

"A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll and Wilkinson in a companion letter in this issue." It was the proof that there really was a Big Bang.

In the following decades, three key satellites probed details of the Big Bang. The first was COBE, launched in 1989, which successfully detected ripples in the background radiation produced by the seeds on which galaxies grew. The Big Bang theory had triumphed. ■

JARGON BUSTER

The cosmic terms you'll need to understand the Big Bang

COSMOLOGICAL REDSHIFT

A stretching of light, or other electromagnetic radiation, caused by the stretching of space between the galaxies as a result of the expansion of the Universe. This is not a Doppler effect, because it does not involve motion through space, but is measured in units of velocity. The cosmic background radiation is light from the Big Bang with a redshift of 1,000.

HUBBLE'S LAW

Actually first discovered by Georges Lemaître, the law says that the redshift 'velocity' of a galaxy is proportional to its distance. So a galaxy twice as far away is receding twice as fast, and so on. This does not mean we are at the centre of the Universe, however. The law works the same way whichever galaxy you observe from.

MICROWAVES

Microwaves are radio waves that, in astronomy, are used to study the background radiation left over from the Big Bang. On Earth, they're used in microwave ovens, radar and telecommunications. The Universe is essentially a microwave oven with a temperature of -270.3°C.

THE UNIVERSE

A STORY IN SIX CHAPTERS

The evolution of the Universe has been a process marked by several clear stages. STUART CLARK is your guide

The year 2009 could go down in the astronomical textbooks as the one when a revolution in our understanding of the Universe began. The iconoclast at the centre of this upheaval is not a person but a machine: a space probe called Planck. Named after the great German physicist Max Planck, the spacecraft was launched by the European Space Agency (ESA) that year, tasked with detecting the 'blueprint' of the Universe – a snapshot of the seeds of the stars and galaxies that surround us today.

For a century, cosmologists have been busily constructing mathematical theories that describe the story of the Universe from the earliest moments to the present day. But now, analysis of Planck's blueprint is revealing a number of plot holes, or 'anomalies' as the scientists call them, that don't seem to fit the story.

For one thing, data from Planck indicates that the Universe is older than expected by about 50 million years. It also

“At one minute old, the entire Universe resembled the interior of a star – but on a vast scale”

contains more of the mysterious dark matter and fewer atoms than previously thought. And while these may sound serious, in reality they are the least of a cosmologist's worries.

Much more troubling is the so-called 'cold spot' in the radiation from the early Universe that Planck has recorded – a region that looks significantly colder than current theories allow. Indeed, the temperature pattern across the whole Universe looks strangely lopsided.

New discoveries such as these are shedding new light on the history of our Universe: the story of how we arrived at the cosmos we see around us today.

CHAPTER ONE: THE BIG BANG

The very moment of the Big Bang remains shrouded in as much mystery as ever. It's the point at which the Universe began – space and time were formed and all the matter and energy that we see around us somehow came into existence. Data from the Planck telescope now indicates this happened 13.82 billion years ago. Initially, there were no stars or galaxies, just a hot, dense sea of particles and radiation.

Straight after the Big Bang, space began to expand, spreading out the matter and energy. The trouble is the theory that we use to understand the expansion, Einstein's Theory of General Relativity, will not work at the extreme densities of the Big Bang and so physicists are searching for a way to extend it.

The best template is quantum theory, which deals with the physics of the very small and provides a basis for all the

forces of nature, except gravity. To investigate such a theory, scientists must turn to the Large Hadron Collider (LHC) at CERN in Switzerland, which recreates the conditions thought to have been present in the Universe a fraction of a second after the Big Bang. “The LHC gives us a mini-Universe in the laboratory,” says Dr Anupam Mazumdar, a cosmologist at Lancaster University. While the experiment can show what particles were prevalent in the primordial Universe, theoreticians then have to form a theory to understand them.

String theory is a possible quantum theory of gravity, but it is unclear whether it bears any resemblance to reality, because the mathematics are currently unable to predict anything that can be tested in a laboratory or observed in the Universe. For now, the moment of the Big Bang remains terra incognita.



The Large Hadron Collider fires particles around a 27km (16-mile) ring before smashing them together to recreate conditions just after the Big Bang



The CMS detector at the Large Hadron Collider (top, below) is looking for particles that could make up dark matter

CHAPTER TWO: INFLATION

10-35 seconds post-Big Bang

Until Planck, almost every observation of the Universe's largest scales had suggested that it is remarkably uniform. Sure, there are clusters of galaxies and huge voids, but even these are comparatively small when the Universe as a whole is considered.

As a result, cosmologists had developed a mathematical framework called inflation to explain the uniformity. First proposed in 1980 by Alan Guth, a particle physicist from the Massachusetts Institute of Technology, it postulated that, right after the Big Bang, a period of extraordinary expansion took place. In the blink of an eye, the Universe grew bigger by a factor of at least 1,060. This would smooth out any large-scale deviation across the Universe, making it appear uniform. Only the smallest fluctuations in the density of matter and energy would remain, the cosmologists theorised. Remarkably, these fluctuations were found in 1989 by NASA's COBE satellite and amount to no more than one part in 100,000. They are the seeds from which the galaxies have grown.

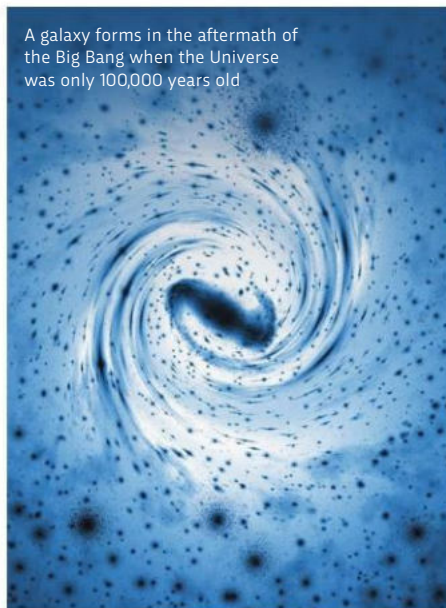
Planck has measured these fluctuations in much greater detail. The £500 million

spacecraft split the sky into a billion pixels and observed each one a thousand times during its three-year mission. This produced a map of the sea of microwaves that bathe all of space – the cosmic microwave background (CMB) – unlike anything that had been seen before.

It is these subtle fluctuations in this radiation left over from the Big Bang that provide astronomers with their blueprint of the early Universe – the distribution of matter and energy a fraction of a second after the Big Bang. When the data from Planck was released, it immediately became clear that there are problems that the cosmological community are still trying to come to terms with.

There is a suspiciously large cold spot signalling that a vast clump of matter was present in the early Universe and it is much denser than inflation can explain. More troubling is that there is one side of the Universe where the fluctuations

A galaxy forms in the aftermath of the Big Bang when the Universe was only 100,000 years old



appear stronger than the other, indicating an uneven distribution of matter across the whole Universe. "This is very strange," says Dr George Efstathiou, Professor of Astrophysics at the University of Cambridge and a member of the Planck science team. "And I think that if there really is anything to this, you have to question how that fits in with inflation. It's really puzzling."

But it may not spell the end for the theory of inflation just yet. "Instead, my gut instinct is that these anomalies will point to a more specific model of inflation," says Dr Rose Lerner, a cosmologist at the University of Helsinki

in Finland who works independently of the Planck consortium.

Another solution to the anomalies, according to Matthew Kleban of New York University, is that during the sudden expansion that happened during inflation, our Universe slammed into a neighbouring one. This sent shockwaves rippling through our cosmos that imprinted the anomalies we see today. If so, we should think of them as a cosmic bruise. Testing such a controversial idea, however, is very tricky.

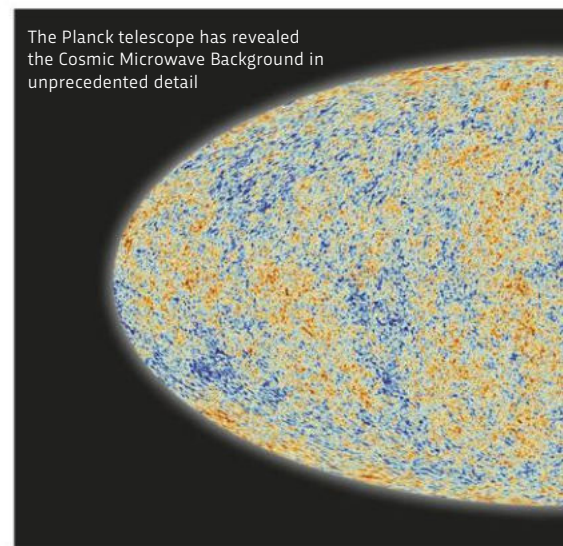
CHAPTER THREE: PARTICLE CREATION

1 minute post-Big Bang

At one minute old, the entire Universe resembled the interior of a star – but on a vast scale. Particles that would become the nuclei of all the atoms in the Universe were built in this cauldron. Mostly these were single protons that would become hydrogen, but around a quarter of the particles transformed into helium nuclei, containing two protons and two neutrons. There were also trace amounts of lithium and beryllium produced.

The evidence for all of this furious activity is all around us today in the chemical make-up of the Universe. We know from measurements of the radiation given off by our Sun and other stars that 98 per cent of the Universe remains in the form of this primordial hydrogen and helium. Only 2 per cent of the original atoms have been processed into heavier chemical elements while inside stars.

The Planck telescope has revealed the Cosmic Microwave Background in unprecedented detail



CHAPTER FOUR: THE DECOUPLING OF MATTER AND ENERGY

380,000 years post-Big Bang

This is the moment when the radiation detected by Planck was released into space. Until then, the Universe had been a searing mass of atomic nuclei, lighter particles and energy. It had been impossible for whole atoms to form; whenever a nucleus and an electron particle bonded together, the torrent of radiation smashed them apart again.

Now, the continual expansion of space had weakened the radiation so much that it could no longer break apart the atoms. This was a watershed moment because, with most of the previously free particles now confined into atoms, it was as though the fog cleared.

In the same way that we are able to see to the horizon on Earth on a clear

day, Planck has enabled us to now see this radiation that has spent in the region of 14 billion years travelling across space, preserving a record of the density of the various clumps of matter that became galaxies. It's this record that now provides troubling insights into the inflation that went before.

CHAPTER FIVE: THE COSMIC DARK AGES

1 million years post-Big Bang

Initially, the decoupled radiation would have been visible to the human eye – not that, of course, there were any humans around to see it. But the continued expansion of space stretched the radiation into the infrared and then into the microwave.

The Universe became dark. Even after a million years, there were no celestial objects, so no sources of light. These were the Cosmic Dark Ages. Slowly, the sea of atoms across the Universe began to fragment into clumps, pulling themselves together to become the first celestial objects. This was driven by the gravity of 'dark matter' clouds composed of particles that formed shortly after inflation.

The Cosmic Dark Ages ended with the first celestial objects. The first stars were purely hydrogen and helium, and some could have been thousands of times the mass of the Sun. They lived for just hundreds of thousands of years before destroying themselves and seeding the Universe with the heavier elements needed to form planets and life.

In March 2013, the Hubble Space Telescope pinpointed one of the Universe's

CHAPTER SIX: PRESENT DAY

13.8 billion years post-Big Bang

Occasionally, galaxies still collide and merge, but these incidents are a pale fraction of the number of cosmic smash-ups that used to take place. Star formation is also significantly reduced in the modern

Galaxies might not collide as often as before, but the Universe remains far from boring

oldest stars right on our celestial doorstep. Known as the Methuselah star, it has an estimated age of 14.5 billion years – give or take 0.8 billion years. It's only this margin of error that means it's potentially consistent with the supposed age of the Universe. This might sound like the star is older than the predicted age of the Universe, but it's more of a quirk of how accurate we are able to measure the age of a star. It is speeding through space, just 190 light-years away.

The first black holes were those now found at the centres of galaxies. Although a black hole emits no light, matter falling into its gravitational clutches does heat up and emits radiation. They would have ended the Cosmic Dark Ages as surely as the first stars.

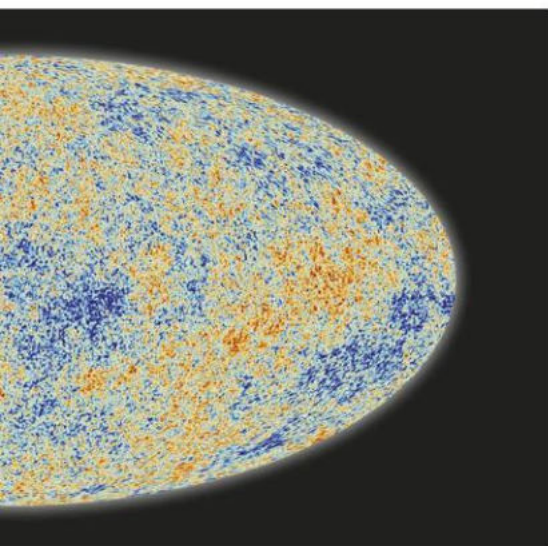
The first galaxies, known as quasars, were voracious monsters. Their feeding black holes gave out as much light as their collections of stars. Gradually, the black holes consumed all the matter in their vicinity, leaving only the stars to shine within the galaxy.

Universe. But don't go thinking that the Universe became boring.

The biggest mystery for cosmologists to solve manifested itself about five billion years ago. A strange energy began to accelerate the expansion of the Universe. Astronomers call it dark energy, but just don't ask them to explain it, yet.

"We're nowhere near to understanding what it is," admits Dr Tony Padilla, a cosmologist at the University of Nottingham. Taking quantum physics as a starting point predicts a strength for dark energy that is monstrously large compared to what is observed. "It really makes no sense, and it's a problem that's been swept under the carpet for too long," says Padilla.

But maybe not for much longer: ESA is busy developing the Euclid mission, slated for launch in 2020. It will investigate, with extreme precision, the way in which the Universe is expanding in order to determine the exact effect of dark energy, thus providing an important clue as to what it is. Clearly, the story of the Universe has not yet reached its conclusion. ■



UNRAVELLING THE FABRIC OF THE UNIVERSE

ROBERT MATTHEWS investigates how the structure of space could shed light on black holes, the Big Bang and the nature of reality itself

There's no doubt it would be the most mind-boggling journey imaginable, the ultimate deep dive – a journey not to the bottom of some oceanic abyss, but into the very fabric of the cosmos itself. Scientists are embarking on a grand project to explore the apertures of space in search of a realm whose properties could transform our view of the nature of reality.

It's known as the Planck scale and it exists at levels far smaller than the tiniest atom or even subatomic particle. Named after Max Planck, the German physicist who pioneered quantum theory more than a century ago, nearly everything about the

Planck scale beggars belief. Today's best microscopes can achieve magnifications of around 100 million times, which is just about enough to reveal individual atoms. To do the same for events on the Planck scale, you'd need a microscope 10 million billion billion times more powerful still. Put another way, you'd need magnifications so great that individual atoms would appear bigger than entire galaxies.

Yet, despite the challenges involved, scientists believe they're closing in on the Planck scale. They've already come up with some insights by exploiting cosmic events as awe-inspiring as the challenge itself. And some suspect the first glimpses of the stitches in the fabric of the Universe may

emerge from experiments that are underway right now.

The results may explain some of the deepest mysteries in science – including the birth of the Universe from an incredibly compact state, nearly 14 billion years ago. “The structure of space-time is the new and perhaps last frontier on our way to a complete understanding of nature,” says theorist Professor Martin Bojowald of Penn State University. “The Planck scale is crucial for our understanding of the Big Bang and what's at the centre of black holes.”

According to Prof Bojowald, scientists may now be standing at the edge of a whole new view of reality as profound as that which followed the proof of the existence

of atoms just a century ago. “We now know what the atomic nature of matter implies, but for space-time we’re still working at a level comparable with 19th-Century physics,” he says. “If Planck scale effects can be detected, we can test and improve our theories about it.”

CHANGING IDEAS

While attempts to reach the Planck scale are at the cutting edge of 21st-century science, suspicions about the true nature of space and time date back millennia. In the 5th Century BC, the Greek philosopher Zeno of Elea argued that the ‘common sense’ notion of space and time being infinitely divisible leads to paradoxes. He pointed out that if space is infinitely divisible, the very idea of moving from one point to another becomes problematic. Yet in everyday experience, there doesn’t seem to be a problem – which suggests there may be something wrong with the idea that space is infinitely divisible.

Glimmerings of quite what the problem is didn’t emerge until the mid-1950s, when theorists began attempting to unify the two great theories of modern physics: quantum theory, which governs the subatomic world, and Einstein’s theory of gravity, known as General Relativity.

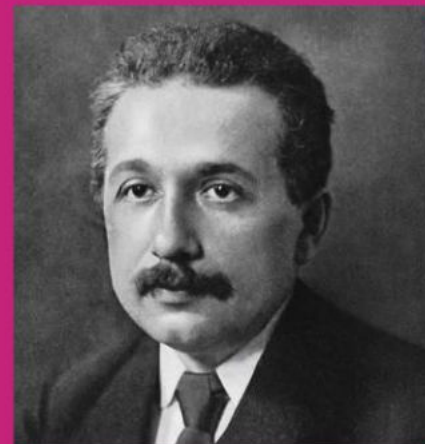
Theorists had recognised that only such a unified theory could explain the mystery of the Big Bang, when the whole of the Universe had burst forth from some unimaginably compressed state. By itself,

Einstein’s theory of gravity was not up to the job: its equations simply went haywire when trying to describe the instant of the Big Bang. But theorists suspected that when combined with quantum theory, General Relativity might start to give sensible answers again. Rough calculations suggested that the resulting theory of ‘quantum gravity’ no longer implied that the Universe started out with literally no size at all. Instead, it suggested that the cosmos emerged from a state of incredibly small but finite size roughly equal to the Planck scale.

But the implications of quantum gravity don’t stop at the Big Bang. They affect the nature of space and time right here and now – through the combined effect of Einstein’s theory of gravity, plus the famous quantum uncertainty principle.

According to this, certain properties of apparently empty space are intimately connected. In particular, the more precisely a region of space is defined, the more uncertain its energy content becomes. Einstein’s theory of gravity predicts that this will lead to space-time becoming ever more distorted. As the level of distortion increases, the smaller the volume of space becomes, reaching its most extreme at the Planck scale.

“If something is localised to a region smaller than this scale, the gravitational warping is likely to be so great that the entire region is engulfed in a mini black hole,” says quantum gravity expert Professor Ted Jacobson of the



BEYOND EINSTEIN

The quest for a Theory of Everything

One of the biggest questions surrounding the Planck scale is what happens to space and time down there. One idea is that it will take the form of space-time foam, like the surface of a wind-swept sea. But most believe the truth will only emerge if physics’ Holy Grail is found: the Theory of Everything (ToE).

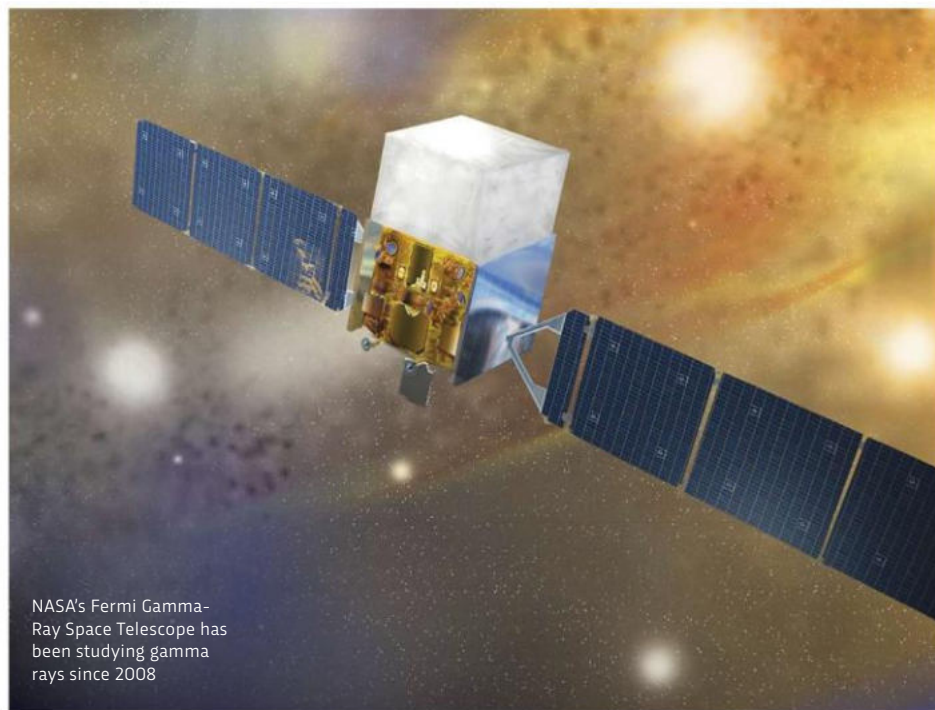
The quest began exactly a century ago, when Einstein tried to develop a single set of equations to describe the forces of both gravity and electromagnetism. He never found his ‘unified field theory’ – which, in any case, failed to incorporate forces of nature discovered later.

Now, theorists think they know how to create a ToE: combine Einstein’s theory of gravity, known as General Relativity (GR), with quantum theory, the rules of the subatomic world. The challenge lies in marrying their different approaches to describing fundamental forces.

Attempts to combine these approaches soon ran into mathematical problems. But in the mid-1980s theorists made a breakthrough. Many of the problems disappeared if everything, even space and time, is made up of ‘superstrings’.

These multidimensional objects are thought to have two key properties. They’re incredibly small: roughly the same size as the Planck scale. And they have at least 10 dimensions, of which six are curled up into incredibly complex shapes known as Calabi-Yau manifolds.

Superstrings seem to solve the problems of unifying quantum theory with GR. Together, these properties point to a new vision of the ‘fabric’ of the cosmos. At the Planck scale, space wouldn’t be smooth and regular, but nor would it be chaotic. Instead it’d be like a vast plain dotted with the Calabi-Yau manifolds.



NASA's Fermi Gamma-Ray Space Telescope has been studying gamma rays since 2008

STUDYING THE FABRIC

How the Hubble Space Telescope acts like a giant 'microscope'

In 2011, a team of scientists led by Fabrizio Tamburini at the University of Padua, Italy attempted to detect Planck scale effects using the power of the orbiting Hubble Space Telescope (HST). To do it, the team analysed images of quasars, the incredibly bright central regions of galaxies on the edge of the visible Universe. As they lie billions of light-years away, these quasars should appear as sharp, if faint, point-like objects. But in travelling across the vastness of the Universe, their light should be affected by the existence of any Planck scale effects in the fabric

of the cosmos. And because the effect is cumulative, by the time the light reaches the Earth, the images should be increasingly blurry.

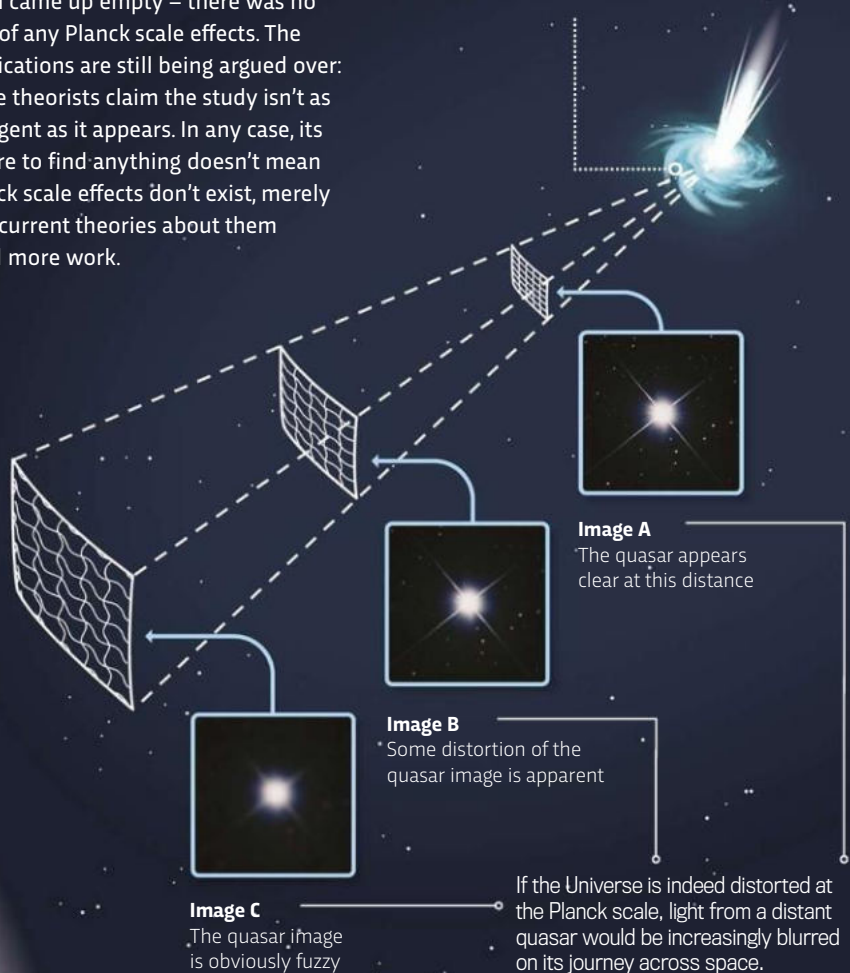
After analysing the images of over 150 quasars taken with the HST, the team came up empty – there was no sign of any Planck scale effects. The implications are still being argued over: some theorists claim the study isn't as stringent as it appears. In any case, its failure to find anything doesn't mean Planck scale effects don't exist, merely that current theories about them need more work.

Quasar

A very bright galaxy powered by a supermassive black hole

Hubble Space Telescope

The space-based instrument receives light from the quasar



460BC

1899

1915

1955

KEY EVENTS

A brief history of our understanding of space-time

Zeno of Elea shows how the idea that distances can be infinitely divided leads to paradoxes, hinting that 'common sense' views of space may be misleading.

German physicist Max Planck puts forward a fundamental and incredibly small unit of length – the Planck scale, now recognised as the scale at which space loses its 'common sense' properties.

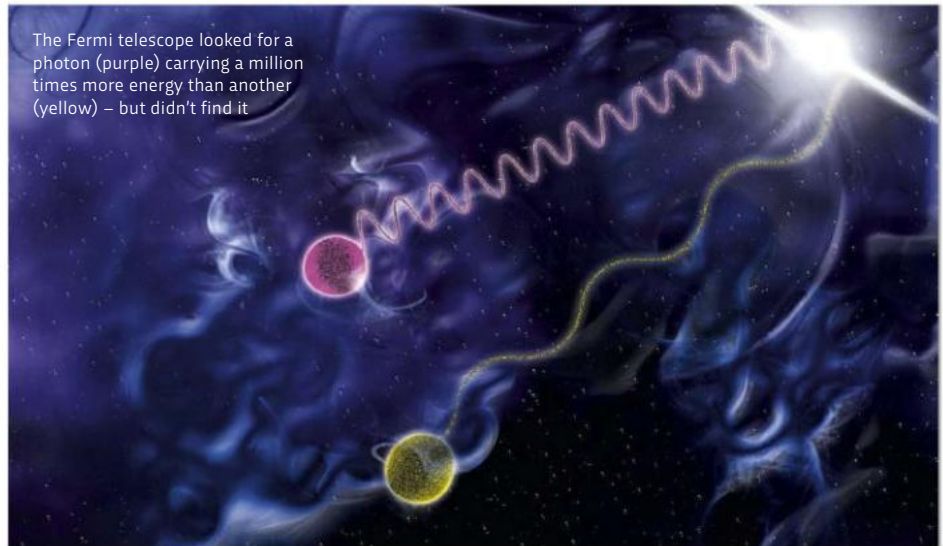
Albert Einstein publishes his theory of gravity, known as the General Theory of Relativity, which reveals a fundamental connection between space, time and the force of gravity.

➔ University of Maryland. “So at the Planck length scale, space-time is warped in the extreme.”

A QUESTION OF SCALE

The details of what happens to the fabric of the cosmos down at this scale aren't clear, and various scenarios have been put forward. But most suggest that right now, all around us, space and time are undergoing unimaginable contortions on the Planck scale. At least, they are if quantum theory and relativity still hold at that level. But that isn't guaranteed by any means, Prof Jacobson cautions.

“If they don't hold, something else very exotic – transcending our current understanding – would be going on,” he



“For space-time, we’re still working at a level comparable to 19th-Century physics”

says. “Either way, things are likely to be ‘interesting’ at the Planck scale.”

There's only one way to discover just how interesting it is: devise some methods for probing the nature of space and time down there. And, astonishingly, scientists have already come up with ways of doing just that – with tantalising results.

Ironically, so far most progress has been made via studies of events that take place on truly titanic scales. The reasoning is simple enough: even the tiniest effects can be made detectable if they're given the chance to accumulate. And, in the case of Planck scale phenomena, that means looking for their telltale signs in events at huge distances from the Earth.

It's a strategy first tried out by astronomers using NASA's Fermi space telescope. Launched in 2008, Fermi is able to detect gamma rays – the most penetrating form of radiation unleashed by the most violent events in the Universe. In May 2009, Fermi detected a two-second

blast of gamma rays coming from a galaxy over seven billion light-years away. Among the radiation making up this blast, astronomers detected two rays whose wavelength – and thus energy – differed by a factor of a million. This made them perfect for testing one theory about the Planck scale: that the contortions may be so violent that they violate Einstein's famous rule that all radiation travels through empty space at the speed of light.

Some theorists have claimed that the result would be significant differences in speed, according to the energy of the radiation. Yet despite the huge contrasts in their energy, the two gamma rays struck Fermi's detector within 0.9 seconds of each other – after a journey lasting over seven billion years. According to Fermi scientist Peter Michelson of Stanford University, California, that's bad news for theories about the Planck scale that try to undermine Einstein's venerable theory. “These two photons travelled at the same

speed, to one part in 100 million billion,” he says. “Einstein still rules.”

THE SEARCH CONTINUES

Since then, scientists have conducted several more searches for Planck scale effects. Dr Philippe Laurent of the Saclay research centre in France and his colleagues published a study of gamma radiation detected in 2004 by the European Space Agency's Integral satellite. According to some, Planck scale distortions of space and time should put a detectable twist, or polarisation, into the gamma rays as they travel through empty space. Yet Dr Laurent's team were unable to find any evidence of polarisation in the gamma rays – ruling out another swathe of theories.

A team led by Fabrizio Tamburini at the University of Padua, Italy published a study looking for Planck scale ‘fuzziness’ in images of distant galaxies taken by the Hubble Space Telescope. The implications of the results remain hotly debated, but it seems that they too have succeeded only in ruling out some theories of the Planck scale.

So, could the search for the stitches of space-time prove to be a wild goose chase? Nobody knows yet. Einstein's century-old concepts may prevail – or they may collapse to reveal an astonishing new vision of the nature of space and time. ■



1985

American theorist John Wheeler posits the concept of space-time foam: the roiling turbulence of space and time expected at the Planck scale, according to some theories.

2008

Theorists trying to combine Einstein's theory of gravity with quantum theory produce new views of the nature of space and time at the Planck scale, such as the Calabi-Yau manifold.

2011

Astronomers using the Fermi orbiting observatory detect gamma rays from an explosion halfway across the Universe. Their behaviour shows no evidence of Planck scale effects.

Attempts to detect Planck scale effects by studying radiation from exploding stars and distant galaxies draw a blank, raising questions about some theories of Planck scale phenomena.



THE NATURE OF GRAVITY

What goes up must come down... But why that's the case is a mystery that took some of humanity's greatest minds centuries to figure out. And, as BRIAN CLEGG explains, some aspects of gravity continue to remain a puzzle



There are four fundamental forces that operate in the Universe: the strong nuclear force, the weak nuclear force, the electromagnetic force and gravity. Gravity is the most obvious of these – yet it has proved a very difficult puzzle to crack.

To the ancient Greeks, gravity reflected the nature of the elements. Aristotle described how earth and water had gravity, and there was a tendency of motion towards the centre of the Universe (Earth). Air and fire, he said, had levity, which encouraged them to move away from the centre. But these tendencies were only present in the imperfect, sub-lunar realm. In the Greek world view, everything from the Moon upwards depended on the fifth element – quintessence – which allowed the heavenly bodies to rotate undisturbed.

To understand Aristotle's viewpoint, we need to forget all we learned about physics at school. Gravity was not a force – it simply described the nature of earth and water. It was their natural tendency to seek out the centre of the Universe, just as it is a dog's natural tendency to fight cats. Although gravity would be refined over the years, there were few serious challenges to Aristotle's domination of the physical sciences for 2,000 years.

DOWN TO EARTH

The great 7th-Century Indian mathematician Brahmagupta briefly flirted with the idea that gravity might work in a similar way to a magnet, as did the Islamic scholar al-Biruni 300 years later. But this wasn't enough to shake Aristotle's theoretical dominance. The first cracks appeared with the transformation of the Solar System by Copernicus and Galileo. If they were correct – that Earth travelled around the Sun, making that the new centre of the Universe – then Aristotle's model of gravity fell apart. Based on

IN A NUTSHELL

The ancient Greeks thought that earth and water were drawn towards the centre of the Universe, then believed to be Earth. But thanks to Galileo, Newton and Einstein, our knowledge of this fundamental force has come a long way since the 4th Century BC.

reasoning rather than observation and experiment, Aristotle's ideas required the Earth to be the centre of the Universe. If it were the Sun instead, all heavy matter should fly off into space.

What's more, Aristotle's model of gravity made heavy objects fall faster than light ones. With more material in them, the heavy objects should feel a stronger urge and therefore move faster. Aristotle stated this as fact, yet Galileo demolished the idea. He asked what would happen if you tied together two objects of different weight. The heavier weight, according to Aristotle, would want to fall faster and would speed up the lighter one – but the light weight should slow down the heavier one, leaving them falling at an intermediate speed. Yet the combined object was heavier than either, so the whole should fall faster. It didn't make sense.

Although Galileo almost certainly didn't, as legend has it, drop weights off the Leaning Tower of Pisa to discover that they arrived at the ground at the same time, he did experiment with pendulums

proportional to its quantity. The apple draws the Earth, and the Earth draws the apple. But more than this, Newton made the leap of proposing 'universal gravitation'. He broke Aristotle's lunar barrier and applied the same force throughout the Universe, realising that gravity was responsible for keeping the planets in their orbits, where otherwise they would fly off in a straight line.

All this and more Newton included in his masterpiece, *Philosophiæ Naturalis Principia Mathematica*, usually known as the *Principia*. The book itself, originally written in Latin, is not easy to read and relies far more on geometry than we would expect today, but here we get the key understanding that the force of gravity is dependent on the masses of the objects involved divided by the square of the distance between them. This and his laws of motion were enough for Newton to describe the way that planets and moons move and the way that things fall when they drop. It was, without doubt, a triumph.

“Newton realised gravity was responsible for keeping the planets in their orbits, stopping them flying off in a straight line”

that had bobs made of cork and lead, one “more than 100 times heavier” than the other, and showed that they swung (and hence fell under gravity) at the same rate. He also repeatedly rolled balls down sloping channels to measure the effects of gravity. And Galileo explicitly described a ‘force of gravitation’ that pulled weights towards the Earth.

But it was Isaac Newton who brought gravity fully under the auspices of science and mathematics. It's not clear whether he was truly inspired by seeing an apple fall (it certainly didn't fall on his head), even though he did make this claim. In a long chat with the antiquarian William Stukeley in April 1726, the elderly Newton described how the fall of an apple made him think, “Why should the apple always descend perpendicularly to the ground?”

In Stukeley's account, Newton says that the apple is pulled by a ‘drawing power’ to the Earth, and that this force must be

However, Newton did leave one aspect hanging – how this strange force acting at a distance could work. In *Principia*, he writes ‘hypothesis non fingo’, translated as ‘I frame no hypothesis’. This was a sly comment: in using the word ‘frame’, as in framing someone, Newton was suggesting that his competitors were making things up. Still, this gap in explanation left Newton open to attack, particularly for his use of the word ‘attraction’. Today we are familiar with ‘attraction’ being applied to gravity, but at the time it was only used in the romantic sense. He seemed, to 17th-Century ears, to be saying that the Earth orbited the Sun due to some kind of planetary crush.

Newton had not worked in isolation. His great rival Robert Hooke, for instance, had suggested that gravity was an ‘inverse square law’ that reduced with the square of the distance, but Hooke had been unable to manage the maths to

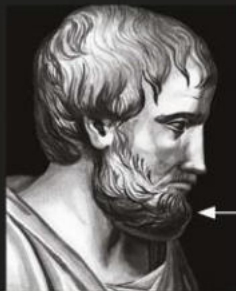


CAST OF CHARACTERS

Five great thinkers whose work was crucial in shaping our understanding of gravity

Galileo Galilei
(1564-1642)

This natural philosopher believed in the importance of experiment and, as a result, dismissed Aristotle's ideas on gravity. Though famous for being tried for promoting the Copernican model of the Solar System, Galileo's greatest contribution was his methodical exploration of mechanics and motion, including the influence of gravity.



Aristotle

(384-322 BC)

The definitive ancient Greek philosopher, Aristotle set the agenda for science for more than 1,800 years. This is a pity, as his theories – based on reasoning rather than observation – were almost universally misleading. Gravity as Aristotle saw it was a tendency for heavy things to prefer the centre of the Universe.



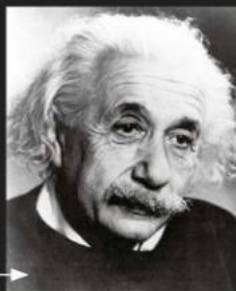
Isaac Newton
(1643-1727)

The greatest English physicist. Most of his work on light, motion, gravity and calculus was done in Cambridge, though much was achieved when he was confined to his home in Lincolnshire due to the plague. He was later an MP, Master of the Mint and President of the Royal Society – but physics remains his most significant legacy.



Albert Einstein
(1879-1955)

Einstein was born in Ulm in Germany, though he was a Swiss citizen from his teens. He produced three papers in 1905, while working in the patent office, that would lay the foundation of quantum theory and establish Special Relativity. His theory of General Relativity from 1915 is still the standard theory of gravitation.



Arthur Eddington
(1882-1944)

Born in the Lake District, Eddington worked as an astronomer and astrophysicist in Cambridge. When asked if it were true that only three people in the world understood the theory of General Relativity, Eddington is said to have replied, "Who is the third?".



support his idea. It took Newton to assemble the magnificent whole.

GRAVITY EXPLAINED

Despite his protestations, Newton did have some thoughts on how gravity might work. He suspected, as many did, that there was an invisible material in space that could transmit the force. Such mechanical models for gravity became more sophisticated with time. The most popular was that of Nicolas Fatio de Duillier and George-Louis Le Sage, two Swiss scientists who independently developed the idea that space was full of tiny invisible particles that constantly bombarded bodies from all directions. When something got in the way, like Earth, it sheltered other objects from particles coming from its direction. This meant that the remaining particles pushed objects towards Earth.

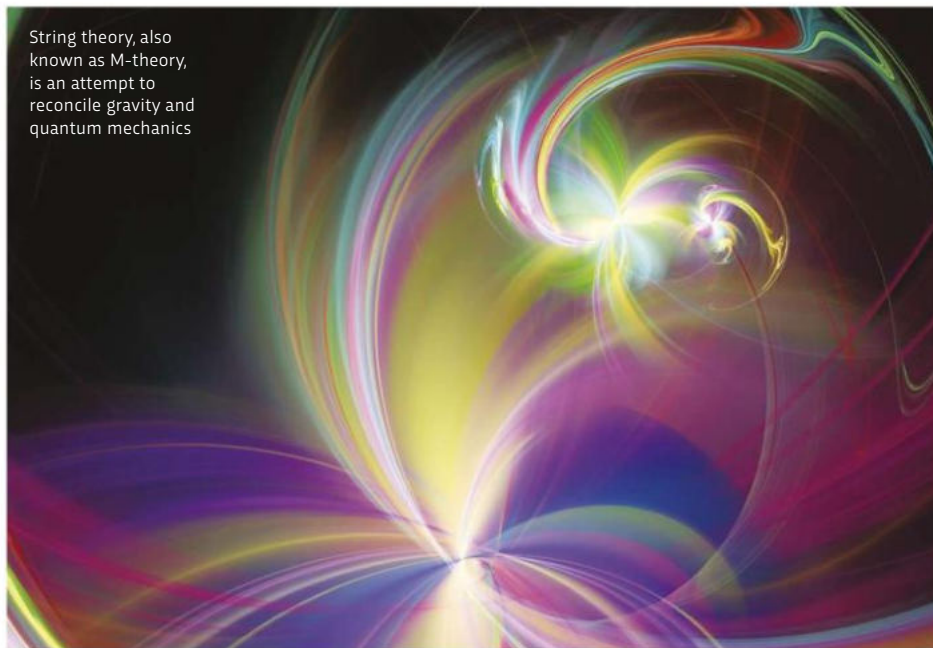
This sounded very unlikely. But it would take the remarkable mind of Albert Einstein to come up with a better suggestion. His breakthrough thought on gravity came shortly after the remarkable year of 1905, when Einstein wrote three papers that transformed physics. These established the existence of atoms, formed the foundations of quantum theory (for which he won his Nobel Prize) and introduced Special Relativity, which showed how apparently fixed quantities like mass, length and the flow of time varied depending on your viewpoint.

Two years later, Einstein was sitting in the patent office in Bern and had what he described as his happiest thought. All of a sudden a thought occurred to me: if a person falls freely, he will not feel his own weight. I was startled. The simple thought made a deep impression on me. It impelled me towards a theory of gravitation."

GRAVITY AND LIGHT

What Einstein had realised was that gravity and acceleration were equivalent and indistinguishable. If, for instance, you were in a spaceship with no windows and found that you were experiencing a pull of 1g, there are two possible explanations. You could be sitting still on the surface of the Earth, or you could be in space and the craft could be accelerating at 9.81 metres per second per second – the same acceleration as due to Earth's gravity. Your instruments could not detect a difference. But if this is true, it tells us something odd about gravity.

String theory, also known as M-theory, is an attempt to reconcile gravity and quantum mechanics



If we imagine a beam of light crossing the accelerating spaceship, the beam will appear to bend to someone inside the ship as a result of its motion. But since acceleration and gravity are equivalent, the same light beam should also bend in a gravitational field. Einstein had realised that gravity warps space, twisting it near a massive body so that anything travelling in a straight line curves around it. This is as true of an orbiting planet as it is of a beam of light.

In fact, his discovery proved stranger still. While the warping of space explains the orbits of the planets, it doesn't tell us why the apple falls. There is no reason for something to start moving. But it is space-time – the mash-up of space and time that emerged from Special Relativity – that is warped by massive objects, and it is the warp that initiates motion. The mathematics to support all this is fiendishly complex – even Einstein had to get help to understand it – but the principle is simple enough.

Einstein had given Newton's theory a framework, a reason for working. More than that, General Relativity, as Einstein's theory became known, made some predictions that were different from those Newton would have expected – and experiments have verified that it is General Relativity that matches reality.

It seemed in many ways that the theory of gravitation was complete. Einstein's development would be used to predict everything from the existence of black holes to the way the Universe changes with time. But there is still one big gap in our understanding. All the other forces

of nature are quantised. They aren't continuous, but are granular with tiny divisions called quanta. The expectation is that there should also be a quantum theory of gravity, but as yet one has not been established. For a while, it seemed as if string theory would provide the answer, but there is increasing concern that this mathematically-driven concept will never make useful predictions, leaving growing interest in alternative theories like loop quantum gravity.

GRAVITY AND US

Our modern understanding of gravity reveals that it's far more important than the ancients thought. Gravity not only keeps things in place on Earth, it was also responsible for the formation of the Solar System as it coalesced out of a spinning cloud of dust and gas. It's gravity that produces the temperature and pressure in the Sun that, along with quantum effects, make it undergo nuclear fusion to generate the heat and light that gives us life.

Experiments in space have even shown that gravity is essential for living things. Plants struggle to grow with no gravity to direct their roots. In an experiment on the International Space Station, it has been shown that birds' eggs need gravity to develop. And human beings deteriorate in low gravity, losing bone density and muscle tone, while lungs suffer compression as organs drift upwards with no gravity to keep them in place.

Gravity continues to keep hold of some secrets. It retains much of its mystique.

JARGON BUSTER

Key terms used when discussing the nature of gravity

FUNDAMENTAL FORCES

The four forces of nature: gravity, electromagnetism and the strong and weak nuclear forces. Between them, they're responsible for all interactions between particles (and between matter and light).

INVERSE SQUARE LAW

This describes a quantity that gets smaller as the square of a value gets bigger. For instance, if you double the distance between two bodies the gravitational pull is reduced by a factor of four.

MASS

A concept introduced by Isaac Newton to describe the amount of matter present. The mass of a body is what causes its gravitational attraction and doesn't vary, whereas its weight is the force of gravity on the mass at a particular location.

RELATIVITY

Galileo observed that motion is relative. If we move at the same velocity as something else, it doesn't move with respect to us. Einstein developed this idea in his theories of Special Relativity (reflecting the effect of the fixed speed of light) and General Relativity, which brings in gravity and acceleration.

We don't know, for instance, why it is so much weaker than the other forces. If you doubt this, compare it with electromagnetism: in picking up a paperclip, a small fridge magnet overcomes all the gravity the entire Earth can muster. Nor do we know how to bring gravity into the quantum fold. But thanks to the work of those pioneers Newton and Einstein, this fundamental force is no longer a total mystery. ■



RELATIVITY ON TRIAL

Just over 100 years ago, Albert Einstein wrote a groundbreaking theory that transformed physics forever. But are there any chinks in its armour? MARCUS CHOWN delves deeper

WHAT IS GENERAL RELATIVITY?

The General Theory of Relativity describes how mass and energy cause the fabric of space-time to warp, giving rise to what we perceive as gravity. This theory expanded on Albert Einstein's earlier Special Theory of Relativity. Both theories are based on the idea that the laws of physics act in the same way everywhere and that the speed of light is constant. From this starting point, Einstein deduced that as everything is moving relative to everything else, different viewers see the same event differently. This is where the theory gets its name.

In November 1915, at the height of World War I, German physicist Albert Einstein published a revolutionary theory of gravity. Not only did General Relativity show that Isaac Newton, arguably the greatest scientist to have ever lived, was wrong, it predicted both the existence of black holes and that the Universe had been born in a Big Bang. It even showed, at least in principle, how to build a time machine.

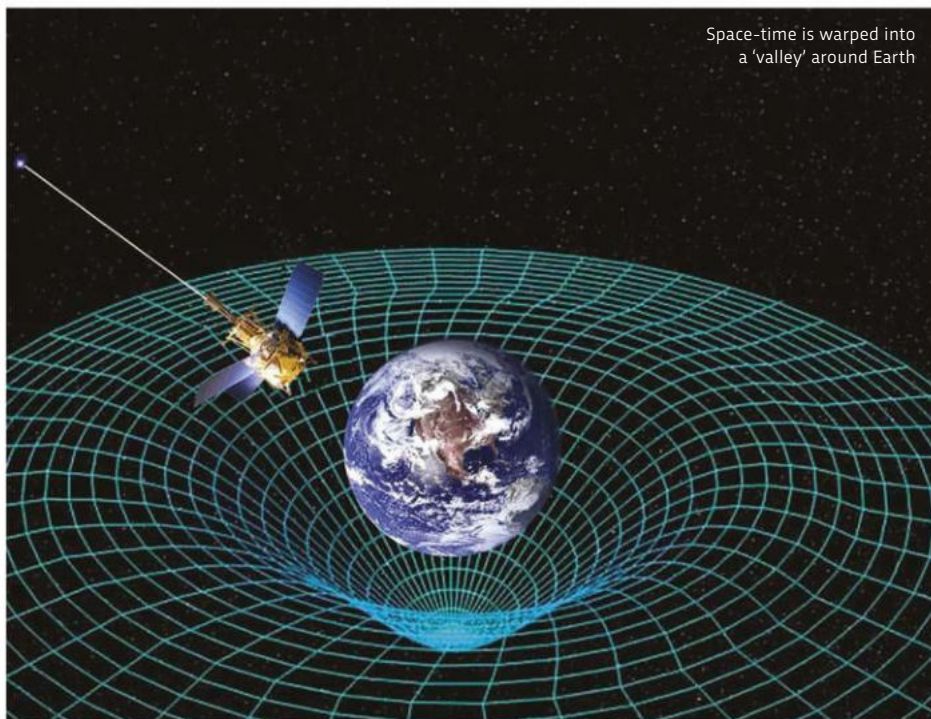
The key thing Einstein recognised is that, in any small region of space, gravity and acceleration are the same thing. He came to this conclusion after considering Galileo's 17th-Century observation that all bodies, irrespective of their mass, fall at

the same rate under gravity, hitting the ground at the same time if dropped from the same height. How could this be?

Einstein imagined a spacecraft far away from the Earth, which is accelerated at $1g$. If an astronaut inside lets go of a feather and hammer from an identical height, the floor accelerates up towards them at $1g$ and both objects hit the floor at the same time. If the windows are blacked out and the astronaut doesn't know they are in space, they might conclude they are experiencing gravity on Earth.

Einstein deduced that we feel gravity because we are accelerating. We do not realise it – and this is the incredible part – because matter warps the four-dimensional space-time it sits in. There is a valley we cannot see in the space-time around Earth. Our 'natural' motion is to take the shortest path, or the path of least resistance, through space-time – that is, to fall to the bottom of the valley. Earth's surface obstructs us, pushing back. This is how we experience gravity.

In a nutshell, this is General Relativity. As theoretical physicist John Archibald Wheeler said: "Matter tells space how to curve. And curved space tells matter how to move." The theory has passed every test in the past century, predicting and explaining phenomena beyond the scope of Newton's theory. But it is known to break down in the 'singularity' at the heart of a black hole and in the Big Bang. So physicists are searching for a flaw that points the way to a deeper, more



Space-time is warped into a 'valley' around Earth



The South Pole Telescope is part of a global array called the Event Horizon Telescope that aims to study the black hole at the Milky Way's centre

PHOTO: SCIENCE PHOTO LIBRARY, ISTOCK X3, NASA, DAN MARRONE/UNIVERSITY OF ARIZONA

→ fundamental concept that will fill in the gaps of Einstein's theory. One key prediction that has yet to be confirmed is the existence of gravitational waves...

CATCHING WAVES

Gravitational waves are ripples in the fabric of space-time, which spread outwards from an accelerated mass like ripples on a pond. The problem is that space-time is about a billion billion billion times stiffer than steel. This means it takes a lot to vibrate it and create gravitational waves. Only the most violent astrophysical events such as the birth or merger of black holes or the collision of super-dense stars are capable of causing vibration.

In December 2015, the European Space Agency (ESA) launched LISA Pathfinder, a mission to test the concept of a space-based gravitational wave detector. The ultimate idea of LISA, which stands for Laser Interferometer Space Antenna, is to put a giant equilateral triangle in space, probably in 2034. The triangle will consist of three satellites, somewhere between one million and five million kilometres apart, bouncing laser light back and forth using mirrors. Think of the sides of the triangle as giant rulers. A passing gravitational wave is expected to alternately stretch space in one direction and squeeze it in a perpendicular direction, so the trick will be to look for subtle changes in the length of the rulers. "We expect to be able to detect change as small as the width of an atom over millions of kilometres," says LISA Pathfinder Project Scientist Paul McNamara.

Gravitational wave experiments have been built on Earth, but background vibrations of the ground mimic real sources, making them blind to the lowest frequency of gravitational waves. Such waves should be detectable by LISA. In addition, there should be a 'background' of tens of millions of events caused by white dwarf-white dwarf binaries in the Milky Way. 'Binaries' are systems consisting of two stars, orbiting a common centre of mass. "There is also a chance that a space-borne detector will be able to directly measure primordial gravitational waves produced in the first split-second of the Big Bang," says McNamara.

"Electromagnetic waves allow us to 'see' the Universe, whereas gravitational waves will allow us to 'hear' it," explains McNamara. "Imagine going to an orchestra recital and only being able to watch the musicians without hearing any sound. Now turn on the



5 WAYS...

...you can see Einstein's theory in real life

MASS

The 'Higgs field' accounts for only about 1 per cent of your mass. 99 per cent is due to a relativistic effect. Specifically, the quarks that compose you are moving so fast they gain mass. Without Einstein, you would weigh only about 1kg!



SUNLIGHT

According to Einstein, mass is a form of energy and so can be converted into other forms of energy. This is what is happening in the Sun's core, where nuclear reactions convert about 0.7 per cent of the mass of hydrogen nuclei into heat and, ultimately, sunlight.



GOLD

An atom absorbs and re-emits light when an electron moves between orbits. The light's energy (colour) depends on the energy difference between the orbits. Gold ought to appear silver, but its innermost electrons move so fast that they gain mass. This changes the light its atoms reflect, making it appear gold.



THE UNIVERSE

The distant Universe seen through telescopes is not actually there: it's an illusion. The reason is that matter creates valleys in space-time which light from distant objects must negotiate on its way to Earth. The Universe is therefore distorted as if seen through frosted glass.



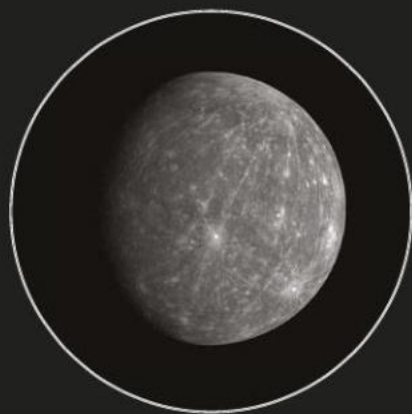
SLUGGISH SATELLITES

If you have a smartphone or sat-nav, it calculates your location relative to a constellation of global-positioning satellites. When these are close to Earth, they experience stronger gravity and their on-board clocks slow. This effect must be compensated for to calculate your location.



GENERAL RELATIVITY'S SUCCESSES

This isn't the first time that Einstein's famous theory has been put to the test

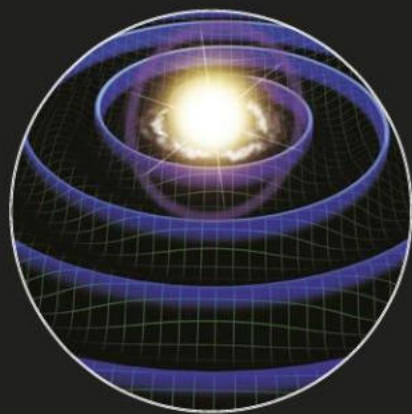


MERCURY MYSTERY

According to Einstein, the gravity near the Sun is stronger than Newton would have predicted, causing the elliptical orbit of Mercury to gradually change its orientation. It 'precesses' – the planet traces out a rosette-like pattern around the Sun. Before Einstein, this was such a puzzle that it led to the suggestion of a planet – Vulcan – tugging on Mercury.

TIRED LIGHT

As light climbs out of the valley in space-time around a massive object like a star, it loses energy. This is equivalent to a reduction in its frequency and is known as a gravitational red shift. It has been observed in the light of dense, white dwarf stars.



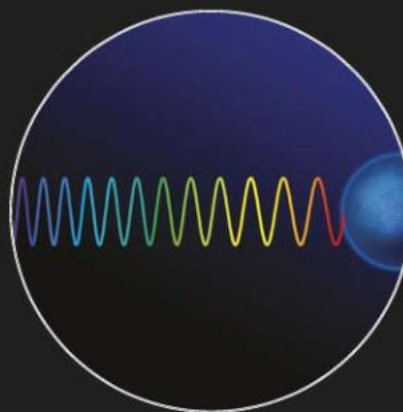
BENT LIGHT

Einstein calculated the Sun's gravity would bend the trajectory of light from distant stars by twice the amount Newton would have predicted. The only way to observe stars close to the Sun is during a total eclipse. During the eclipse of 1919, Arthur Eddington confirmed the positions of stars were shifted – as Einstein had predicted.



RIPPLING GRAVITY

In 1974, Russell Hulse and Joseph Taylor discovered two super-dense neutron stars orbiting each other. They determined they were spiralling together and losing orbital energy. This lost energy is exactly the amount Einstein predicts they should be radiating into space as gravitational waves.



→ sound. This is what it will be like when we start to observe the Universe with gravitational waves." Prepare yourself for the cosmic symphony.

GOING DEEPER

The fact that General Relativity breaks down in the 'singularity' of the Big Bang and a black hole, where the density of matter skyrockets to infinity, is not very helpful in trying to find a deeper, more fundamental theory. The hope is that General Relativity might reveal a chink in its armour in less extreme circumstances. This is the idea behind an Earth-orbiting experiment called Satellite Test of the Equivalence Principle, or STEP, which is seeking NASA funding. "If it gets the go ahead, it could fly in six years," says Paul Worden, one of the originators of STEP in 1971.

The 'Equivalence Principle' is the fancy name for gravity being indistinguishable from acceleration so that all masses fall at the same rate. Since the principle is the foundation of General Relativity, it is a key place to look for an anomaly. Galileo is supposed to have dropped different masses from the Leaning Tower of Pisa, and Apollo 15's Commander David Scott repeated the experiment – with a hammer and a feather – on the Moon in 1971. STEP will suspend four pairs of 'test masses' made of at least three different materials, such as beryllium, niobium and platinum-iridium, and see whether they move relative to each other.

The masses will be inside a tank of liquid helium to insulate them from external temperature fluctuations and surrounded by a superconducting shell to shield them from electromagnetic interference. Microthrusters will counteract the atmospheric drag on the satellite, so the freefall of the test masses will be nearly perfect.

The key to the experiment is that a satellite in Earth orbit is always falling away from its desired straight-line path, but never gets any closer to Earth because Earth's surface perpetually curves away from it. In other words, it is falling forever. This will enable small differences in the rate at which different masses fall to be magnified.

The Equivalence Principle is known to hold to one part in a trillion, but STEP will better that by another factor of a million. All attempts to unify General Relativity with quantum theory involve new forces, which may affect different materials in different ways. "A violation is

“General Relativity might be put to its toughest test within only a year or two”

The LISA Pathfinder mission will test the concept of a space-based gravitational wave detector



basically the discovery of a new force of nature, or something really weird,” says Worden. “If there’s no violation – at least to experimental accuracy – we can rule out a lot of theories of gravity, but not Einstein’s.”

THE ‘HOLE’ STORY

But General Relativity might be put to its toughest test within only a year or two. So far, the theory has been checked only in situations where gravity is relatively weak. Nobody has tested it where gravity is strong – close to a black hole. That could all change when the Event Horizon Telescope (EHT) images the black hole at the centre of our Milky Way, probably in 2017.

The EHT is an array of cooperating radio telescopes that are scattered around the globe. The radio signals recorded at each site are flown together and combined on a computer at Haystack in Massachusetts to simulate a giant dish that’s the size of Earth. The bigger the dish and the shorter the observing wavelength – the EHT is using 1.3mm –

the more it can zoom in on details in the sky.

The trouble with black holes is they are very difficult to see. Stellar-mass ones are too small and the supermassive black holes in the cores of other galaxies – with up to 30 billion times the mass of the Sun – are too far away. Only one black hole is within reach – the one 26,000 light-years away at the centre of the Milky Way. Sagittarius A*, as it is called, will be magnified in size by its own intense gravity. “It will appear as big as a grapefruit on the Moon viewed from Earth,” says EHT scientist Shep Doeleman of the Massachusetts Institute of Technology who is also the leader of the EHT team.

The key thing is to observe the black hole’s event horizon – the point of no-return for in-falling matter and light – and see whether it behaves as predicted by Einstein or even whether it exists. Stephen Hawking suggested it might not. This will test Einstein’s theory in the realm of strong gravity, where it has never been tested before. “An image would allow us to test General Relativity at the black hole boundary but, just as importantly, it would

make the case for the existence of black holes as solid as it is ever likely to be,” says Doeleman. “An image would symbolise a turning point in our understanding of black holes and gravity.”

Doeleman is being modest. It is possible that the first image of a black hole event horizon will be an iconic image to rival the Apollo 8 image of Earth rising above the Moon.

In the world of science, 100 years is an awfully long time. Countless theories have been proposed since Einstein published his famous paper, with many of them turning out to be nonstarters or dead ends. After a century of extraordinary success, it still remains to be seen how far the General Theory of Relativity can be stretched before reaching its breaking point. Could its time be finally up? After all, even Einstein viewed the theory as being incomplete.

If STEP, LISA or the EHT are able to uncover even the tiniest hole in its venerable armour, scientists could be on the brink of formulating a new theory of gravity, or maybe even making the first tentative steps towards the elusive ‘theory of everything’. ■

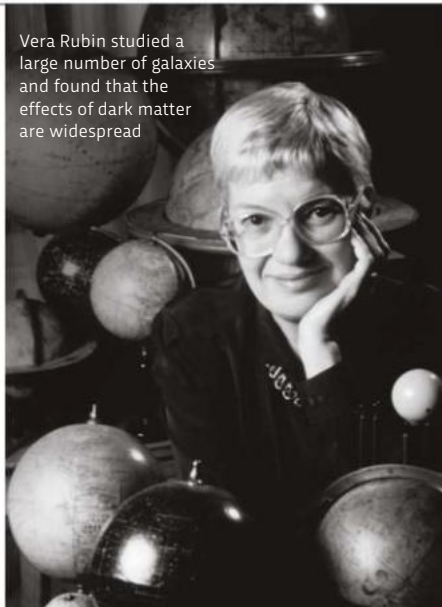
UNDERSTAND DARK MATTER IN 10 MINUTES

For decades, top astronomers have been on an enormous treasure hunt for the Universe's most mysterious substance. But if we can't see it, how on Earth do we know it even exists? COLIN STUART explains...

WHY DO SCIENTISTS THINK THAT DARK MATTER EXISTS?

The first clues that everything in the Universe was not as it seemed came in the 1930s. Swiss-American astronomer Fritz Zwicky was looking at a group of galaxies and working out how fast the individual galaxies were moving. To his surprise, he found them careering around at speeds far greater than he expected. In fact, they were moving so fast that they should have quickly dispersed, breaking away from the gravity of everything else in the cluster. Except they weren't. Zwicky was forced to surmise that there must be more stuff in the cluster that was boosting its overall gravitational pull and keeping the galaxies tied together. The discrepancy wasn't small either. He estimated there was 400 times more matter present than he could see. At a loss to explain what this mysterious material was, he simply called it 'dunkle materie' – the German for dark matter.

Vera Rubin studied a large number of galaxies and found that the effects of dark matter are widespread



At the same time, Dutch astronomer Jan Oort was forced to invoke something similar. He was looking at the stars orbiting near the edge of the Milky Way. He expected to find that the further he looked from the galactic centre, the slower the stars would be rotating around it. This idea isn't dissimilar to our Solar System: the further a planet is from the

Sun, the longer it takes to orbit it. But that's not what Oort found. The outer stars were zipping about faster than they should be. In order to explain why they stayed bound to the Milky Way despite their lofty speeds, he supposed there was some invisible material with gravitational power spread throughout the Galaxy. By 1980, American astronomer Vera Rubin had spotted the same effect in around 100 other galaxies. Whatever this invisible stuff was, it was widespread.

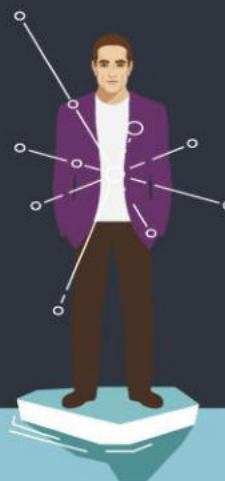
Today, an effect known as gravitational lensing provides even more evidence to suggest there is something strange going on. If we see a large amount of mass, say a cluster of galaxies, move in front of a distant light source, then the foreground object is able to bend the light from the background object around it. This light creates a series of arcs that can join together to form what's known as an 'Einstein ring'. The more mass there is, the greater the amount of bending. Yet there is often not enough visible mass in the cluster to account for the amount



DARK MATTER IN NUMBERS

86

strings carrying detectors were lowered 2,500 metres below the surface of the Antarctic ice as part of the IceCube experiment. This is hunting for evidence of dark matter annihilations.

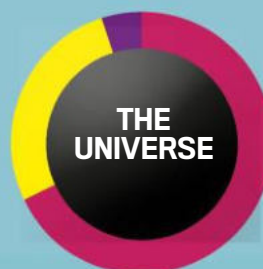


If they exist, billions of dark matter particles are passing through your body every second. Only around 100,000 a year interact with the atoms inside your body.



264,979

litres of water are needed to shield the subterranean Large Underground Xenon dark matter detector from being contaminated by radiation from the Earth's surface.



The Universe is thought to be made of **68 per cent dark energy**, **27 per cent dark matter** and just **5 per cent normal matter**.

13

terraelectronvolts

is the record-breaking energy with which the new souped-up Large Hadron Collider is smashing particles together in an attempt to unlock the secrets of dark matter.

JARGON BUSTER

ANNIHILATION

The process by which two dark matter particles come together, creating a cascade of new particles. We're attempting to detect this with various experiments around the world and in space.

GALAXY

A large collection of stars in space, like a city for stars. Ours is called the Milky Way and has around 200 billion stars.

GRAVITATIONAL LENSING

A prediction of Einstein's General Theory of Relativity, which says that mass bends light. However, astronomers often see more bending than the amount of visible material present would suggest.

NEUTRINO

A small, almost massless particle created by nuclear reactions inside the Sun. Additional neutrinos may be created by dark matter annihilations and detecting them would be a big breakthrough.

STANDARD MODEL

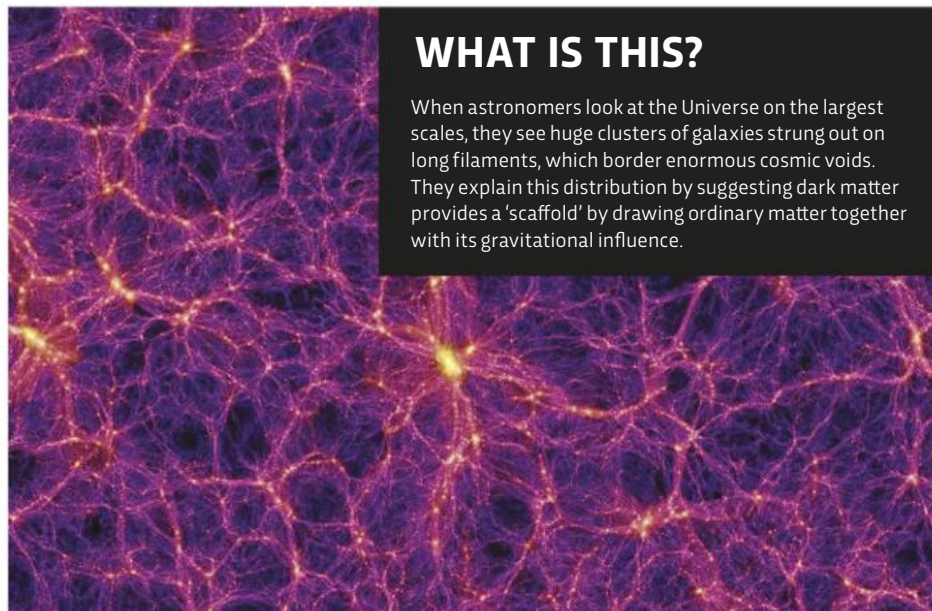
The recipe book that particle physicists use to explain a lot of the subatomic world. It contains rules regarding how particles interact with forces and light.

SUPERSYMMETRY

An idea that goes beyond the Standard Model and says every 'normal' particle has a supersymmetric partner particle. The lightest of these supersymmetric particles could be responsible for dark matter.

WHAT IS THIS?

When astronomers look at the Universe on the largest scales, they see huge clusters of galaxies strung out on long filaments, which border enormous cosmic voids. They explain this distribution by suggesting dark matter provides a 'scaffold' by drawing ordinary matter together with its gravitational influence.



→ of bending we observe. Again, there must be extra mass that's hidden from view.

WHAT DO SCIENTISTS THINK DARK MATTER IS?

Physicists have a cookbook for the Universe known as the Standard Model of particle physics. By using its recipes, they can account for the behaviour of forces and the way particles interact with one another. This model has been validated many times over, including by experiments at CERN's Large Hadron Collider. The book's final missing page was the recently discovered Higgs boson.

And yet there is nothing within those recipes that allows physicists to cook up anything with the observed behaviour of dark matter. It has to be able to interact with normal matter via gravity – and yet in order to remain hidden, it cannot interact with light. In an attempt to explain this behaviour, physicists have come up with a new type of particle: Weakly Interacting Massive Particles (WIMPs). They are 'weakly interacting' because they don't interact with light, and 'massive' because they interact via gravity.

When astronomers run computer simulations of a Universe that evolves with dark matter in the form of WIMPs, they get a structure that is a pretty solid match for the distribution of galaxies that we see today. A theory for physics beyond the Standard Model called supersymmetry also seems to fit with this picture.

Other explanations have been considered in the past, including MACHOs. Standing for MAssive Compact

Halo Objects, the idea is that there are big objects such as black holes ghosting unseen through the Milky Way. When we add up all the mass we can see, we aren't including them, hence why we underestimate the mass of the Galaxy.

WHAT ARE SCIENTISTS DOING TO FIND DARK MATTER?

How do you find something that is, by definition, hidden from view? You certainly can't see it. To make things worse, WIMPs are so ghostly that they almost always pass straight through normal matter – including any detector you build to snare one.

To put it into perspective, dark matter is so abundant that billions of dark matter particles are streaming unhindered through you every single second. And yet, on average, in any five-minute period, only one of these dark matter particles interacts with an atom of normal matter in your body.

This idea that dark matter particles do occasionally deign to interact with normal matter is the basis for the Large Underground Xenon experiment deep under the surface of South Dakota. Scientists have commandeered an abandoned gold mine and set up a dark matter detector 1.6km down. Consisting of 370kg of liquid xenon shielded by 264,979 litres of water, it is designed to pick up the occasional WIMP interacting with the xenon. Should a WIMP recoil off a xenon atom, the atom is accelerated through the liquid, causing a flash that can be



➔ picked up by the surrounding banks of super-sensitive cameras.

Scientists might also be able to detect dark matter when it interacts with itself in a process known as annihilation. When this happens, it is thought a cascade of 'normal' particles is produced and we should be able to pick that up. One such experiment is the Alpha Magnetic Spectrometer (AMS-02) currently strapped to the International Space Station. It is trying to pick up evidence of atomic shrapnel coming from WIMP annihilations near the galactic centre.

The Sun could help too. As the biggest thing in the Solar System it should be acting as a giant cosmic vacuum cleaner, sweeping up dark matter particles as it treks through the Galaxy. Some of the dark matter particles should annihilate inside the Sun, producing a stream of normal particles. Unfortunately, the Sun is so dense that almost all of these daughter particles remain trapped inside. However, one type of particle – neutrinos – would make it out and travel across space to us. Experiments such as IceCube, stationed on Antarctica, are set up to gather these tell-tale signals.

Then there is the Large Hadron Collider (LHC). On 5 May 2015, the experiment began smashing protons together after a two-year shutdown designed to boost the machine's power. It is hoped that, by colliding particles together with greater energy than ever before, nature might begin to reveal more secrets of its inner workings.

COULD DARK MATTER BE SOMETHING ELSE?

So far we've been assuming that dark matter is tangible, something that truly exists. But what if it doesn't? What if it's a phantom – a symptom of the fact that we don't understand gravity properly? That's exactly what proponents of a theory called Modified Newtonian Dynamics (MOND) advocate.

Remember, one of the original reasons dark matter was introduced was to account for the fact that stars in the Milky Way don't slow down the further they are from the galactic centre, unlike the planets of our Solar System. But what if there is one rule for gravity on small scales (like a solar system) and another for large scales (like a galaxy)? While Newton's laws of gravity allow us to send people to the Moon or spacecraft to the planets, stretching those rules to regions to which they don't apply might explain why we're puzzled by the strange motions of stars.

The idea was first put forward by Israeli physicist Mordehai Milgrom in 1983. He suggested that the strength of gravity could become stronger where acceleration levels are small (just like at the edge of a spiral galaxy). These ideas can help to explain some details about how galaxies work in ways that the dark matter theory cannot. However, there is currently no reason to suspect that gravity behaves differently on different scales and MOND struggles to explain why galaxies cluster together in the way they are observed to do.

HAS DARK MATTER GOT ANYTHING TO DO WITH DARK ENERGY?

No. Dark energy is the name given to the mysterious entity thought to be accelerating the overall expansion of the Universe – a sort of anti-gravity. In contrast, dark matter can be thought of as gravitational glue that helps bind galaxies and clusters of galaxies together. The fact they both share the same adjective indicates our collective ignorance about the true nature of both – we're literally in the dark as to what they are.

You can think of the Universe's history as a tug of war between these two dark entities. When the Universe was young,

the galaxies were close together and dark matter dominated – the Universe expanded slowly. Yet as it expanded, the galaxies moved further apart and the collective strength of dark matter on the biggest scales began to wane. Now dark energy is winning the battle and is speeding up the Universe's expansion.

HOW MUCH DARK MATTER IS THERE?

Dark matter completely dominates the ordinary matter of which people, planets and stars are made. Our Milky Way is thought to be about 90 per cent dark matter and only 10 per cent 'normal' matter (also called baryonic matter). Of all of the matter in the Universe, 85 per cent is dark matter and only 15 per cent is baryonic.

There is one thing to be careful of, however, and that's the distinction between how much of the Universe is made of dark matter and how much of the Universe's matter is dark. According to Einstein's famous equation $E=mc^2$, mass and energy are two sides of the same coin. This leads cosmologists to often talk about the mass-energy of the Universe – all the mass and all the energy put together. In these terms, the Universe is 68 per cent dark energy, 27 per cent dark matter and just 5 per cent atoms. If we discount the energy part, the numbers revert to above – 85 per cent dark matter, 15 per cent baryonic matter.

HOW WILL THE HUNT FOR DARK MATTER AFFECT ME?

As with all science research, practical applications can be hard to predict from the outset. However, many technologies often filter down to use in everyday life. Take CERN, for example. The first webpage was info.cern.ch. This technology was devised to communicate between the facility's computers.

One likely spin-off from the dark matter hunt is improved digital cameras. The Large Synoptic Survey Telescope is currently under construction and, by 2021, it should begin to scour the skies from its mountaintop location in the Chilean desert. Equipped with an astonishing 3,200-megapixel camera – the world's largest – it will be able to map out the structure of the Universe in order to test out theories about dark matter. By building such an enormous camera, those new technologies will eventually end up in the commercial photography and medical imaging markets. ■

NOW EXPLAIN IT TO A FRIEND

1 When astronomers look out into the Universe, they see many phenomena that suggest there's more material in the Universe than can be seen with telescopes. Often the gravity in a particular location seems stronger, suggesting some invisible stuff contributing the extra gravity.

2 Since we can't see it, we call this stuff dark matter and it is thought to make up around 85 per cent of all the matter in the Universe. Our best idea of what it is made of is an as-yet-undiscovered particle, called a WIMP (Weakly Interacting Massive Particle) after the properties it would need to have.

3 Experiments around the world and in space are looking for evidence of WIMPs interacting with one another. The search has come up empty, prompting some scientists to turn to an alternative theory called Modified Newton Dynamics (MOND) that suggests gravity varies on different scales.

OUR PLACE IN THE UNIVERSE

Science's greatest minds and centuries of research have tried to position Earth in the ever-expanding Universe. As GILES SPARROW explains, we can now be certain of where we are...

Where do we fit in? For more than 2,000 years, it's a question that astronomers have devoted a great deal of time trying to answer. Each new discovery has brought with it a further diminution of Earth and humanity's place in the cosmos. But those discoveries have also hugely widened our understanding of the Universe as a whole, and helped us establish the precarious position of life on Earth.

Most early 'cosmologies' owed more to mythology than science. But, by the 6th Century BC, ancient Greek philosophers were developing non-mythological theories for the first time. The earliest of these to survive are from Anaximander of Miletus, who argued that Earth was not the centre of the Universe, but instead formed the top surface of a flattened cylinder, floating free in space.

A century later, Philolaus imagined Earth as one of several planets in motion on circular orbits. However, it did not circle the Sun, but instead an unseen and mystical Central Fire. The Sun was

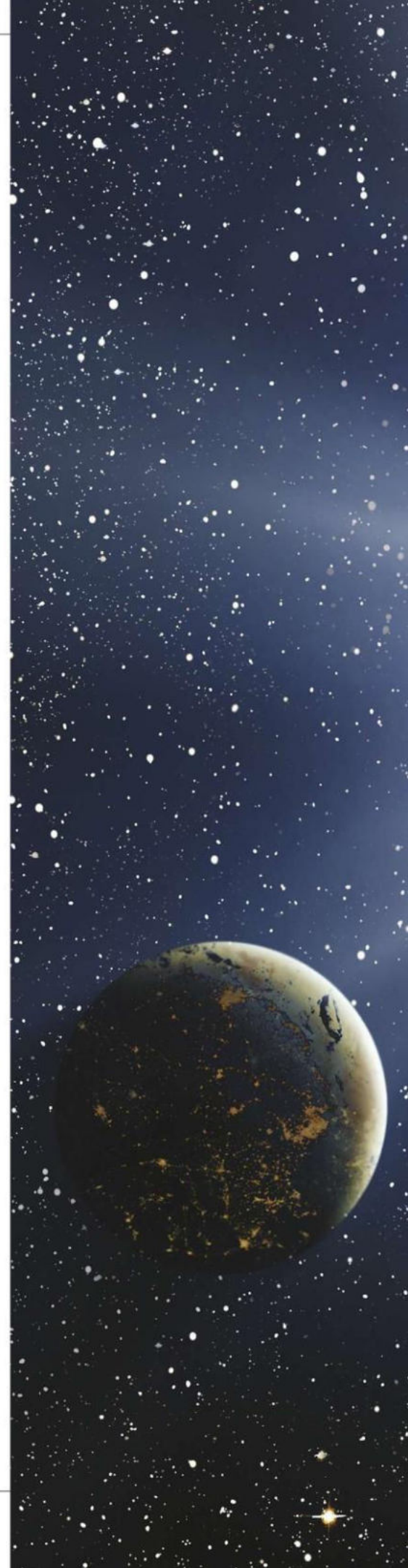
a secondary fire (or perhaps a mirror) following its own orbit around the centre. Philolaus's model was the first theory to suggest that the apparent motion of heavenly bodies derives, at least in part, from the movement of observers on Earth.

By the 4th Century BC, these ideas were undermined by an important realisation. If the Earth is in motion, then surely our view of the heavens should be subject to the same 'parallax' that affects other objects. In other words, just as a nearby tree shifts more rapidly against a distant forest when we change our observing position, shouldn't Earth's orbit through space cause celestial bodies to shift their apparent positions back and forth over time?

For this reason, the great philosopher Aristotle argued that Earth must be the

IN A NUTSHELL

A supernova and a comet in the 16th Century helped astronomers to establish that Earth rotated around the Sun, rather than the other way round. This paved the way for scientists to calculate the true scale of the Universe.



unmoving centre of the Universe. The Central Fire was discarded, and the Sun, Moon, planets and stars set on concentric crystalline spheres that carried them on circular paths around Earth, now understood to be spherical. Aristotle's ideas would hold sway for almost two millennia, despite observations that challenged them.

In the 16th Century, events conspired to break the geocentric stranglehold once and for all. In the early 1500s, Polish priest Nicolaus Copernicus began to develop an alternative heliocentric system that seemed to do a better job.

He was not the first churchman to question the Earth-centred dogma, but his ideas emerged in the midst of a religious Reformation that saw many long-held assumptions questioned for the first time. Copernicus only published the final

version of his work *On The Revolutions Of The Heavenly Spheres* on his deathbed in 1543, but it was swiftly adopted across Protestant northern Europe.

Two cosmic events soon helped the growth of heliocentric astronomy: first, a supernova (exploding star) erupted into view in the constellation of Cassiopeia in 1572. And then, in 1577, a spectacular comet swept through Earth's skies. Danish astronomer Tycho Brahe observed both, showing by their lack of visible parallax that these objects lay far beyond the Moon.

The supernova challenged long-held beliefs about the unchangeability of the stars, while the comet was to prove the key to finally resolving the question of planetary orbits.

Using Tycho's observations, his assistant and collaborator Johannes Kepler worked out that the comet must have followed an elliptical orbit and would therefore have passed through the supposed crystalline spheres supporting the other planets. Kepler went on to model the orbits of the planets themselves as elliptical



TIMELINE

Copernicus introduced the Solar System with the Sun at its centre in the 1540s, turning astronomy on its head



Nicolaus Copernicus publishes his *On The Revolutions Of The Heavenly Spheres*, putting forward a detailed model of a Sun-centred Solar System as opposed to one with Earth at the centre.

1543

1609



German astronomer Johannes Kepler publishes his first two laws of planetary motion in a work called *Astronomia Nova*. By using elliptical rather than circular orbits, Kepler's laws accurately describe the motion of the planets in a heliocentric system.



Friedrich Bessel uses parallax to measure the distance to 61 Cygni, an orange-dwarf binary star some 10.3 light-years from Earth. This provides the first direct confirmation of the enormous scale of interstellar distances.

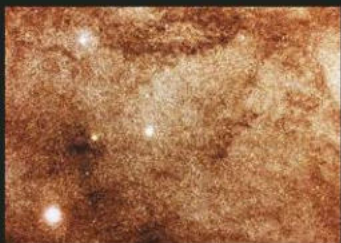
1838

1917



Harlow Shapley maps the distribution of globular star clusters around the Milky Way, showing that our Solar System lies many thousands of light-years from the galactic centre.

Edwin Hubble publishes the first evidence for Cepheid variables in the Andromeda Galaxy. This proves they are not part of the Milky Way – our Galaxy is just one in a possibly infinite Universe.



1924

→ paths around the Sun, and finally produced (from 1609) three laws of planetary motion that provided almost perfect predictions.

Finally, Earth had taken its true place as one of several planets in the Solar System. But it was not until 1671 that Italian astronomer Giovanni Domenico Cassini measured the orbit of Mars and hence determined the true scale of interplanetary space, with tens of millions of kilometres, if not more, separating the planets.

Despite their breakthroughs, Copernicus and Kepler believed that all the 'fixed stars' lay at the same distance from Earth on the interior of a hollow cosmic sphere. One of the first people to doubt this was the British astronomer Thomas Digges, who in 1576 published an almanac popularising Copernican theory in English. He also argued for the existence of an infinite sea of stars scattered at random across space.

By chance, Kepler's discoveries had coincided with the invention of the telescope, and astronomers soon harnessed this new instrument to make measurements with unprecedented precision. Yet all signs of the stellar parallax predicted by the Copernican theory remained frustratingly elusive. As a result, some astronomers remained cautious about this new model of the Universe.

It was Isaac Newton who, in his 1687 *Principia*, settled matters once and for all. Not only did his laws of motion and gravitation provide an explanation for Kepler's laws, but he also made the first plausible estimate of a stellar distance. Based on the assumption that the brilliant star Sirius had the same intrinsic brightness as the Sun, he calculated its distance to be 800,000 times the Earth-Sun distance (12.6 light-years in modern terminology). Newton's figure overestimated Sirius's true distance by 45 per cent but, more vitally, it showed that the parallax of stars must be tiny and that measuring it would be a huge technological and observational challenge.

In fact, it was to be more than 150 years before the challenge was finally met, by the German astronomer Friedrich Bessel. In 1838, Bessel announced he had measured the parallax of a faint star called 61 Cygni (an angle less than 1/5,500th the diameter of the full Moon). By this time, the Earth-Sun distance had been independently calculated, and so simple geometry allowed Bessel to find 61 Cygni's distance – 10.3 light-years in modern terminology.

Following Bessel's breakthrough, astronomers began to build a catalogue of stellar parallaxes, but progress was slow. By the end of the 19th Century, just a few

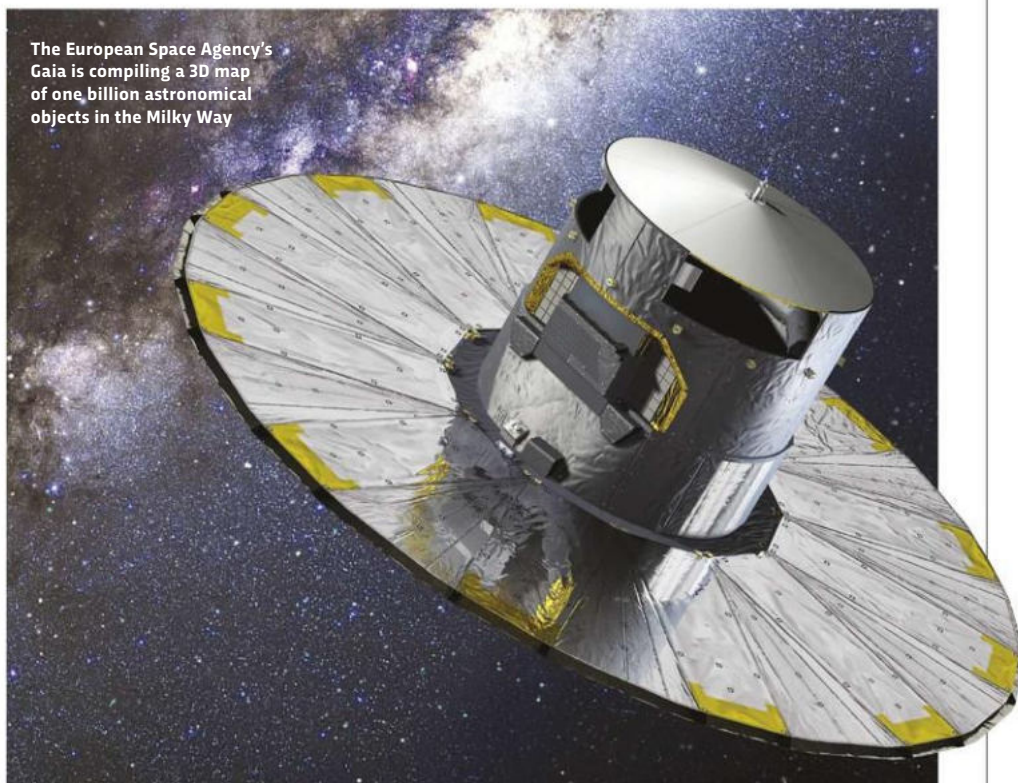
dozen were known with accuracy – it was only with the introduction of photographic surveys that parallax could be measured on a large scale.

Parallax was (and remains) the only way of directly measuring interstellar distances, but it is limited to relatively nearby stars with relatively large shifts. Fortunately, the information provided by direct measurements allowed astronomers to start working out physical properties of stars, such as their intrinsic brightness or luminosity. Contrary to Newton's premise, it soon became clear that stars varied hugely; these variations would offer the next rung on the ladder of cosmic distance.

Comparing the luminosity of stars to the wavelength distribution of their light (crudely speaking, their colours) reveals clear patterns in their distribution that are shown in the famous 'Hertzprung-Russell diagram' of stars' properties. Astronomers can use it to estimate the rough distance to a star based on its 'spectral type' and its apparent brightness in our skies.

It soon became clear that certain stars

The European Space Agency's Gaia is compiling a 3D map of one billion astronomical objects in the Milky Way



NEED TO KNOW

These key terms will help you understand the Universe

1 LIGHT-YEAR

This is a common measure of astronomical distance. It is equivalent to the distance travelled by light, the fastest thing in the Universe, in the course of one Earth year. One light-year is equivalent to 9.5 trillion kilometres (5.9 trillion miles).

2 PARALLAX

This is a perceived shift in the position of a nearby object against a more distant background, caused by a change in the observer's point of view. Accurately measured parallax shifts along a known 'baseline' (the diameter of Earth's orbit) allow astronomers to work out the distance to nearby stars.

3 STANDARD CANDLE

A standard candle is any class of astronomical object or event whose intrinsic luminosity is fixed, or that can be calculated without prior knowledge of its distance from Earth. By comparing the luminosity of a standard candle with its apparent brightness as seen from Earth, astronomers can calculate its distance, and the distance of any larger system of which it forms a part.

display other properties that are very closely linked to their luminosity. Such stars are known as 'standard candles', because they can provide a light source of known luminosity that can be used to find cosmic distances far beyond the reach of parallax.

The first standard candles were used to map the scale of the Milky Way. It had long been recognised that the distribution of stars around the sky was uneven. As early as 1781, William Herschel had attempted to map the Galaxy's shape, and pinpoint our place within it, by counting the number of stars in different directions. But, like Newton, he assumed all stars were of roughly the same brightness and ended up with a flawed model in which the Sun lay near the centre of the Galaxy.

It wasn't until 1908 that the American astronomer Henrietta Swan Leavitt recognised that a class of stars – Cepheid variables – had fluctuating brightness with a period linked to their intrinsic brightness. Using these stars, fellow American Harlow Shapley mapped the position of the Milky Way's globular clusters. These dense balls of stars lie above and below the Galaxy's central plane. He found that they appeared to be concentrated in orbit around a region tens of thousands of light-years from Earth in the direction of the constellation Sagittarius. He reasoned that this was probably the centre of our Galaxy, with the Sun just one unremarkable star in the surrounding stellar disc.

Based on the measured size of the Milky Way, it was now assumed that our Galaxy effectively encompassed the entire Universe, while others argued that the faint 'spiral nebulae' seen in many parts of the sky were galaxies in their own right, viewed across a vast gulf of intergalactic space. This debate was settled in the mid-1920s by Edwin Hubble, who pinpointed Cepheid variables within several spiral nebulae. Based on their periods of variability, Hubble showed that they were intrinsically bright, appearing faint only because we see them over a distance of millions of light-years.

What's more, Hubble identified an important relationship between the distance of these galaxies and the properties of their light – the further away a galaxy is, the more its light is stretched or 'red shifted'. This relationship, known today as Hubble's Law, is a consequence of the general expansion of space in the aftermath of the Big Bang. Since the vast majority of galaxies are far too distant to identify individual Cepheid variables within them, the law is often reversed to provide a rough estimate of a galaxy's distance based on its red shift.

These two essential techniques – parallax and standard candles – remain the bedrock of much astronomical research. Our place in the cosmos might seem increasingly insignificant, but at least we can be far more certain of where we stand. ■

THE SOLAR SYSTEM

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THE HISTORY OF THE SOLAR SYSTEM

Our little corner of the Universe is the product of billions of years of planetary evolution. ELIZABETH PEARSON explains...

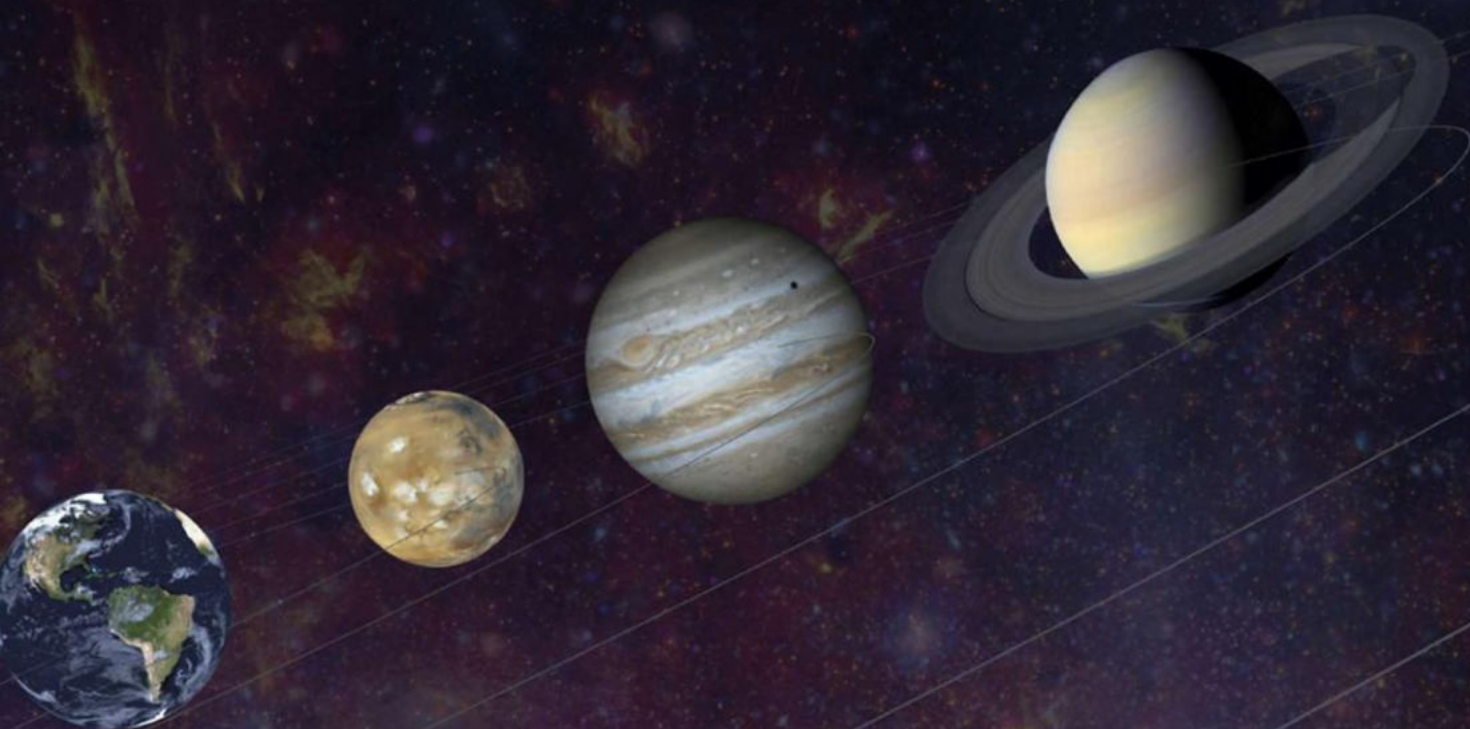
Five billion years ago, something was stirring out in space: a huge cloud of hydrogen and helium was collapsing. The gas rushed towards the centre of the mass, fusing together until it burst into life as the star that we now know as the Sun.

As the Sun was forming, so were the planets. Before our star was born, another larger one had died in a supernova, filling the cloud with gas and dust. This debris gradually formed a protoplanetary disc – a huge, flat ring comprising hundreds of lumps of rock and ice known as planetesimals.

These planetesimals were the building blocks of the Solar System. After a few million years of crashing and melding together, these bodies began to resemble the planets as we know them today.

Close to the Sun, temperatures were too high for volatile chemicals, such as water, to remain solid in any quantities. The initial protoplanetary disc contained only a small amount of rocky solid material, so the four planets that formed closest to the Sun were comparatively small.

But, 730 kilometres from Earth, at what is now the outer edge of the asteroid belt, temperatures were cool enough for gases to form thick atmospheres around rocky cores, creating the gas giants – Jupiter, Saturn, Uranus and Neptune.



“When the infant Earth collided with another young planet, a huge plume of debris was trailed behind”

It wasn't just planets forming, though; several moons did, too. Though many moons are former planetesimals that were captured by a planet, a few – including our own – had a much more violent beginning. When the infant Earth collided with another young planet, a huge plume of debris was trailed behind. After a few hundred million years, it melded together to create our planet's largest companion.

By four billion years ago, the planets and moons had formed, but the Solar System still looked very different from its current state. There were probably many more planets than the eight we know today and they would have been much closer together.

Over time, the outer planets began to move slowly away from the Sun, throwing the gravitational forces of the Solar System off balance. The result was that several early planets were thrown out into deep space and, around four billion years

ago, the remaining debris was pelted against the planets.

This period, now known as the Late Heavy Bombardment, left scars that can still be seen on the faces of the Moon, Mars and other rocky planets. On Earth, such craters have been hidden by the actions of volcanism or worn away by the atmosphere.

The most significant relic left on our planet from that bombardment is the array of elements left behind. During Earth's formation, metals such as gold and copper sank to the core, so the deposits we find in the crust today must have arrived on asteroids and comets at a later date.

Perhaps the most important delivery to our planet was water. The early Solar System was far too hot for water to settle but, by the time of the Late Heavy Bombardment, temperatures had dropped significantly. When comets crashed into

the surface of the early planets, water didn't boil off immediately but instead formed oceans.

After hundreds of millions of years, the planets had settled into their orbits and began to grow and evolve. Volcanism shaped their surfaces while, deep inside, molten cores began to cool. The cores of the smaller terrestrial planets solidified; without the flow of metallic cores, their protective magnetic fields faded, leaving their atmospheres unshielded from solar winds. As time progressed, such differences between each world became exaggerated, leading to the variation in planets that we see in the Solar System today.

And the process is far from over. Comets and asteroids still pelt the planets and the Sun is slowly expanding and becoming brighter. In another few billion years, the Solar System will have transformed itself once again. ■

FROM THE SUN TO THE MOON

*The essential facts and figures from
the near part of our Solar System...*

THE SUN

Distance from Earth: 150,000,000km (average)

Atmosphere: 70 per cent hydrogen, 28 per cent helium, 2 per cent 'metals'

Diameter: 1,390,000km

Fact: The Sun contains more than 99.8 per cent of the Solar System's total mass

MERCURY

Distance from the Sun: 46,000,000km (at its closest)

Atmosphere: 42 per cent oxygen, 29 per cent sodium, 22 per cent hydrogen, 6 per cent helium and 0.5 per cent potassium

Diameter: 4,880km

Visits: NASA's Mariner 10 visited three times between 1974 and 1975. Messenger has been in Mercury's orbit since 2011

Fact: Mercury's temperature varies dramatically. Its proximity to the Sun means it can reach 427°C during the day. At night, though, temperatures can drop as low as -183°C

VENUS

Distance from the Sun:

108,200,000km (average)

Atmosphere: 95 per cent carbon dioxide, plus nitrogen, sulphuric acid and traces of other elements

Diameter: 12,103km

Visits: The first spacecraft that successfully visited was Mariner 2 in 1962. More than 20 missions have visited since, including Venera 7, the first probe to land on another planet

Fact: Venus rotates so slowly that one day equates to 243 Earth days

MOON

Distance from Earth: 384,400km (average)

Atmosphere: virtually none

Diameter: 3,474km

Visits: First visited by Soviet mission Luna 2 in 1959. Apollo 11 was the first manned Moon landing, which took place 10 years later

Fact: The Moon is actually moving away from Earth, pulling away from us at a rate of almost four centimetres each year

EARTH

Distance from the Sun: 149,600,000km (average)

Atmosphere: 78 per cent nitrogen, 21 per cent oxygen and 1 per cent other gases

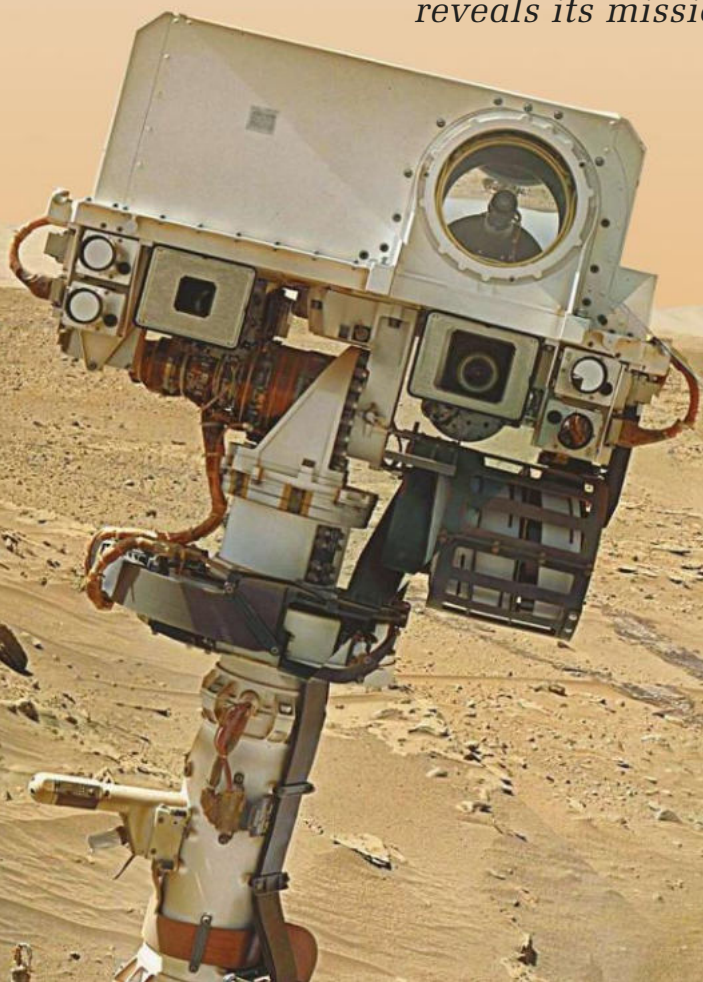
Diameter: 12,756km

Fact: Experts estimate that more than 99 per cent of species that have lived on Earth are now extinct

Please note: the sizes of – and distances between – planets are not in proportion

CURIOSITY THE JOURNEY SO FAR

In August 2015, the Curiosity rover celebrated its third year on Mars. CATHERINE OFFORD reveals its mission highlights to date



899

kilograms is Curiosity's weight. It carries fuel, mechanical arms, cameras and multiple units of highly specialised equipment

1

Aug
2012
LANDING!

After the most complicated rover landing in history (one that relied on a 'supersonic parachute' and 76 pyrotechnic devices), Curiosity arrives at Gale Crater, Mars. It snaps its first view and sends it back to Earth.

2

Sept
2012
DISCOVERY!

Curiosity takes snaps of a streambed, later named 'Hottah' after the Canadian lake. Its discovery prompts speculation that there were once waterways over this part of Mars. Analysis of the streambed indicates that the water was probably between ankle- and hip-deep.

3

Dec
2012
DISCOVERY!

From soil analysis, Curiosity finds clear evidence for water on Mars. It also finds sulphur and chlorine, along with small quantities of organic molecules that are not found naturally on Earth. Concerns are raised about contamination of the testing equipment.

4

Mar
2013
DISCOVERY!

Just weeks after Curiosity tested its drill on the surface of the planet, NASA announces that an ancient Mars could have supported microbes. The first samples contain many 'building blocks' of life, including carbon, hydrogen, oxygen and nitrogen.

5

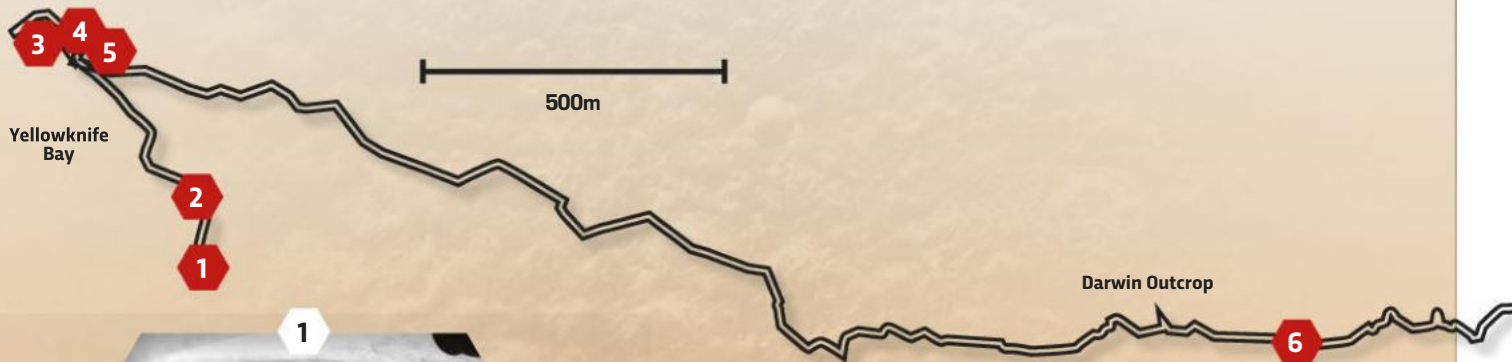
Apr
2013
HOLIDAY!

Curiosity settles in for a few weeks by itself, as communications are made difficult by Mars moving behind the Sun. But although Curiosity isn't allowed to drive or drill, it can still analyse the samples it's already collected.

6

Nov
2013
DISASTER!

Curiosity has been travelling across the Gale Crater. It takes some images of its wheels, which show visible damage – probably caused by rocks.


90

metres can
be travelled by
Curiosity per hour

2

6

Unlike the Mars rover Opportunity, which ran on solar power, Curiosity is powered by the radioactive decay of plutonium fuel that it carries on board



7

Dec
2013

DISCOVERY!

NASA reports that radiation levels on Mars are similar to those on the International Space Station, so Mars visitors might not suffer severe health effects.

8

Jun
2014

ONE YEAR OLD!

Curiosity snaps a selfie at Windjana. The photo celebrates the rover's first birthday (in Martian years). By now, it has travelled more than 10km in total.

9

Sep
2014

PHOTO OP!

Curiosity arrives at Mount Sharp's base, which it will explore over the next few months, gathering data about the planet's geological history. It snaps some pictures of a hole it has drilled.

10

Dec
2014

DISCOVERY!

Curiosity detects local spikes in methane, a gas associated with microbial activity on Earth. Although non-biological processes, like reactions between water and rock, could have produced the gas, it sparks excitement about the possibility of life on Mars.

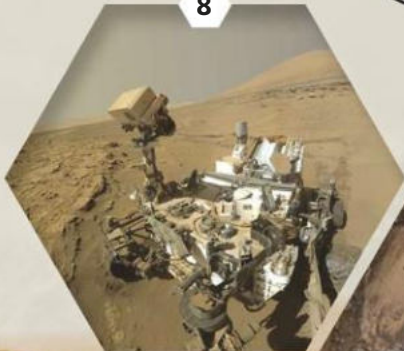
11

Feb
2015

DISASTER!

While transferring a sample, one of Curiosity's arms short-circuits. The rover's operations are paused while NASA investigates. A couple of weeks later, Curiosity is sieving rocks with its arm again.

8



7

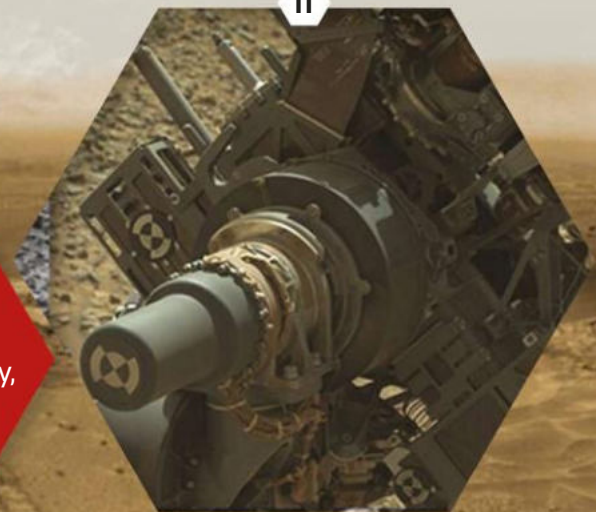
Dingo Gap

The Kimberley Outcrops

9



11



Curiosity has already exceeded its two-year life expectancy. Its predecessor, Opportunity, is still going strong since landing in January 2004

12

Apr
2015

PHOTO OP!
Curiosity snaps colour photos of a Mars sunset (pictured left). The Sun appears to glow blue because of 'light scattering' by clouds of dust in the air. The images will help scientists learn more about Mars's atmosphere.

13

May
2015

1,000 SOLS!
Curiosity celebrates 1,000 Mars days, or 'sols', since it landed. The main image on this page was stitched together from several photos and shows the rover's tracks leading back towards the distant landing site.

12

\$2.5bn

is the amount that the Curiosity project cost. The mission is part of the Mars Science Laboratory



WHAT NEXT?

In September 2016, Curiosity should be joined on Mars by InSight, a lander studying the planet's early evolution. In four years' time, Curiosity's successor Mars 2020 will arrive

Windjana

8

9

Hidden Valley

10

11

12

Pahrump Hills

13

The rover communicates with Earth via 'orbiters' – small satellites that orbit Mars and relay signals back to Earth

FROM MARS TO SATURN

Our factual lowdown on the Solar System continues, taking in both the Red Planet and Saturn's rings...



MARS

Distance from the Sun: 227,940,000km (average)

Atmosphere: 95 per cent carbon dioxide, 3 per cent nitrogen, 1.6 per cent argon, with some water vapour. Trace levels of methane were discovered in 2004

Diameter: 6,805km

Discovered: It's visible with the naked eye, and Nicolaus Copernicus theorised that it was a planet in the mid-16th Century

Visits: Mars is the planet that's been subject to most missions. Probes were first sent by the Soviets in 1960. The existence of water ice was confirmed by the Phoenix spacecraft in 2008

Fact: The tallest mountain in the Solar System is found on Mars. It's a volcano called Olympus Mons that stands 21km high



ASTEROID BELT

Distance from the Sun: The belt covers a distance from 329 million km to 478 million km from the Sun

Composition: Most of the belt's billions of asteroids are made of rock, but some contain iron and nickel metals

Discovered: Astronomer Guiseppe Piazzi first noted Ceres in 1801. Pallas was later discovered, followed by many other asteroids. Ceres has since been classified as a dwarf planet – the only one in the entire asteroid belt

Visits: In March 2015, the NASA spacecraft Dawn entered the orbit of Ceres

Fact: The average distance between objects in the asteroid belt is an astonishing 965,606km, about 24 times the Earth's circumference

JUPITER

Distance from the Sun: 778,500,000km

Atmosphere: 90 per cent hydrogen, almost 10 per cent helium, traces of ammonia, sulphur, methane and water vapour

Diameter: 143,000km

Discovered: While visible in the night sky to the naked eye, it took Galileo's telescope, in the early 17th Century, to spot four of Jupiter's largest moons

Visits: Pioneer 10 was the first craft to conduct a flyby of Jupiter in 1973, followed by Pioneer 11 a year later. Subsequent missions have included Voyager, Ulysses, Cassini and New Horizons

Fact: Jupiter's Great Red Spot is actually an ongoing storm that measures as much as 40,000km across. Estimates suggest it's been raging for as long as 350 years



SATURN

Distance from the Sun: 1.4 billion kilometres.

Atmosphere: 75 per cent hydrogen, 25 per cent helium, traces of methane and water ice

Diameter: 116,474km

Discovered: Like Jupiter, Saturn is visible without telescopes or binoculars, but it wasn't until 1610 that Galileo identified its now-instantly recognisable rings

Visits: Pioneer 11 conducted the first flyby of Saturn in 1979. Voyager 1 and 2 carried out further studies in the 1980s. Cassini-Huygens entered Saturn's orbit in 2004 and is still circling the planet

Fact: Saturn boasts 62 moons. These moons' gravity marshals the planet's rings (made from pure water ice) into coherent, defined objects



Please note: the sizes of – and distances between – planets are not in proportion



PHOTO: NASA X2

ROSETTA

THE JOURNEY CONTINUES...

WILL GATER looks back at the discoveries of ESA's mission to Comet 67P/Churyumov-Gerasimenko

Surprise and serendipity have always been one of the great joys of exploration – precious moments of insight or understanding that reveal the beauty, and perhaps even the eternal mystery, of the Universe we inhabit. For the scientists working on ESA's Rosetta mission, 2015 brought more than its fair share of unexpected excitement. One need only look at the images the spacecraft returned the previous summer to see this extraordinary drama writ large.

Rosetta was launched in March 2004. Its aim was to rendezvous with and eventually orbit the nucleus of a comet, a periodic visitor to the inner Solar System known as 67P/Churyumov-Gerasimenko. Astronomers had expected the 4km-wide lump of ice and dust to look a little bit like a potato, with a few large bumps sticking out here and there.

But as the probe neared its target in July 2014, the comet produced a major surprise: images from Rosetta's cameras showed that rather than being a single and broadly-round body, 67P was comprised of two huge interconnected 'lobes'. "It's just nuts," says the mission's project scientist Matt Taylor, reflecting on the discovery of the unusual shape.

at the comet showed rough outcrops and towering cliffs covering its craggy body, while high-resolution pictures from Rosetta's OSIRIS instrument revealed enormous boulders strewn across the surface. Where the two lobes met, the probe's cameras even revealed an unusual, smooth region flanked by steep escarpments. "I heard a number of comet experts noting the similarities to other cometary bodies that we have observed," explains Taylor. "We have aspects of all other comets rolled into one."

This a view echoed by Carsten Guettler, part of the OSIRIS team. "Comet Wild-2 showed the pits that we are also seeing now; Tempel-1 showed cliffs, which manifest as terraces on 67P. There are smooth, dust-covered regions that were expected from dust fall."



SPECTACULAR VIEWS

By August, the views from the spacecraft were even more spectacular. Dramatic monochrome images taken by the spacecraft's navigation camera on arrival



Rosetta was launched from French Guiana in 2004, 10 years before its rendezvous with 67P



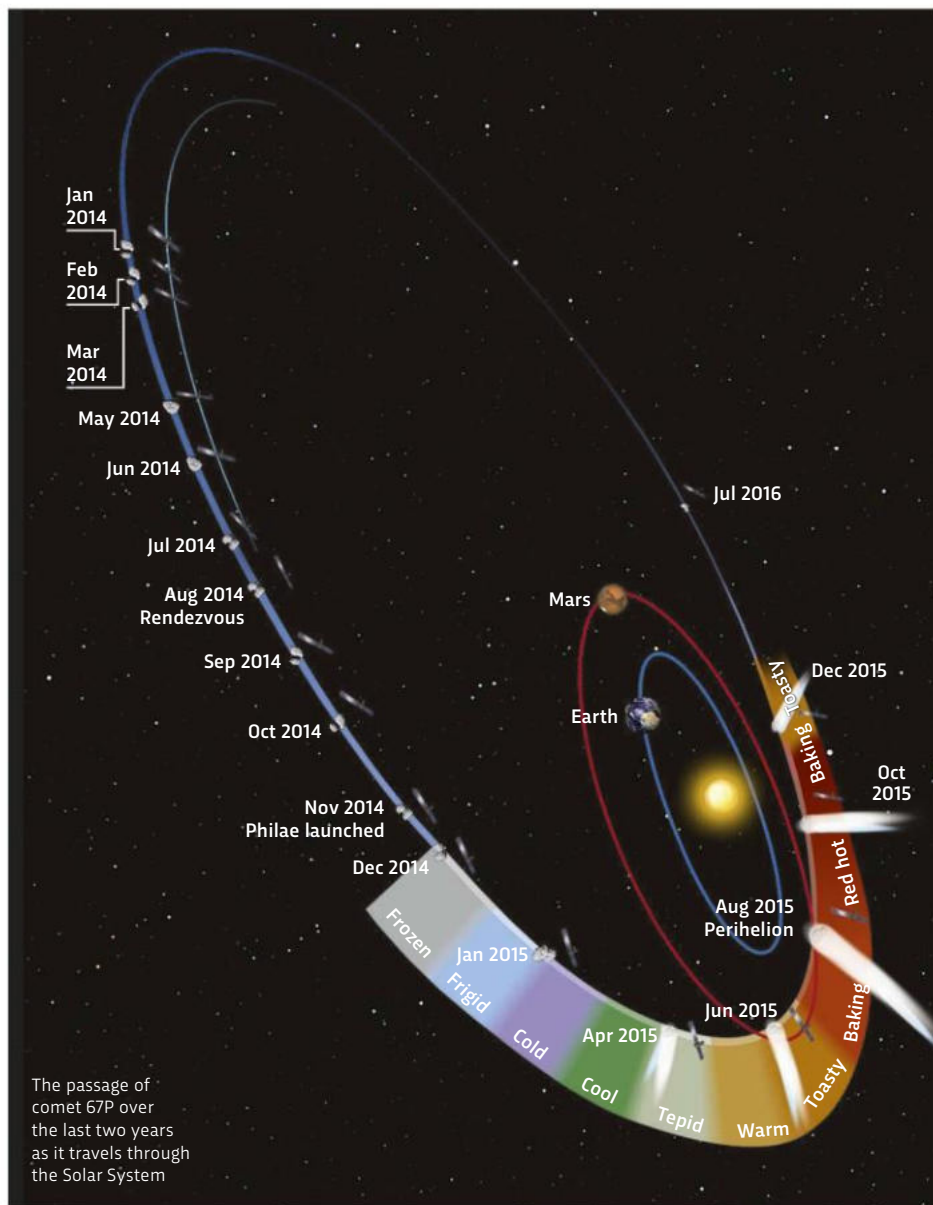
“On the other hand, we expected to see at least some impact craters, but now we don’t. Did the comet not experience as many collisions as we expected or were they all washed out from the activity? We have many ideas on how the activity shapes the surface, how it is connected to cliffs, fractures, pits and flat lands. The one theory to combine all these ideas while being consistent with all that we see and know will take a lot of time.”

IN FOR THE LONG HAUL

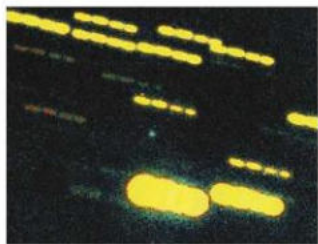
Thankfully time is something that the Rosetta team has had a great deal of. Rather than being a fleeting flyby mission, the spacecraft has stayed close to 67P since its arrival. That’s allowed the scientists to not only scrutinise the surface in detail but also watch how the comet changes and evolves as it nears the Sun.

“What we are doing hasn’t been done before,” explains Taylor. “We predicted how things would be but, as usual, things don’t always go to plan. We had expected it to be dusty, but the dust environment is much more complex than we expected. As such, we are unable to navigate very close to the comet as the star trackers, necessary for accurate pointing, get confused when there is a lot of dust around.”

Despite these difficulties, Rosetta has been hard at work analysing the comet and the material it’s been giving off. “These measurements indicate the comet is very old and has spent a long time in the outer parts of the Solar System,” says Taylor. “This puts all other measurements into context – they are all of a very primordial body, made at the time of Solar System formation and not perturbed much since.”



TIMELINE



January 2003

A MISSED OPPORTUNITY

Rosetta had been due to visit the comet 46P/Wirtanen, but concerns about the rocket means that the mission misses the launch opportunity.

March 2004

LIFT-OFF!

Rosetta eventually blasts off from Kourou, French Guiana, on 2 March. Now it is heading for an entirely different comet, 67P/Churyumov-Gerasimenko, which had been discovered in 1969.



20 January 2014

THE SPACECRAFT AWAKENS

After several years of travelling through space in a state of electronic hibernation, Rosetta is woken up. It is soon taking its first long-distance images of 67P.

Mid-2014

BURN, BABY, BURN

For the past few months, Rosetta has been making a number of thruster ‘burns’ that are necessary to ensure it makes a successful rendezvous with 67P. Some burns have lasted up to seven hours.



While Rosetta provides valuable observations as it buzzes around the comet, the mission design also incorporated a plan to get a close-up view of 67P. In November 2014, the orbiter deployed a small lander, named Philae, resulting in one of the most thrilling spacecraft descents ever seen in planetary exploration. And although the initial landing didn't quite go to plan, the probe did return unprecedented images and data from the surface of the comet.

Back in orbit, Rosetta tried to pin down Philae's location but, as the weeks went by, it was also witnessing something incredible on the comet. 67P was becoming more and more active as it approached perihelion, the closest point in its orbit to the Sun.

Jean-Baptiste Vincent, from the Max Planck Institute for Solar System Research, had been studying the activity of 67P long before Rosetta arrived at the comet. "At that time, I was working more on large-scale coma structures observable from Earth," he says – the 'coma' being the haze of dust and gas enveloping the comet's central nucleus. As Rosetta closed in on the comet, Vincent and his colleagues – working with the spacecraft's OSIRIS instrument – began to see activity increasing at their destination.

MYSTERY OUTBURSTS

"The first sign was that the comet was not a single point light source any more, like in our early images from March 2014," recalls Vincent, "but that it had developed a coma. This was expected, but still nice to see. Much more surprising was the big outburst we observed at the end of April 2014, with the sudden release of about 10 tonnes of cometary material. We still do not know what triggered this event."

With Rosetta flying around 67P, OSIRIS's cameras have been regularly keeping watch for changes on the comet. "Our modelling predicted that activity would arise mainly from high northern latitudes on the nucleus around the time Rosetta reached the comet," says Vincent. "While our predictions were correct, we quickly realised that the large scale jets are really made of many much smaller structures."

Perhaps most excitingly, several of those smaller structures appeared to be associated with huge 'pits' in the surface of the comet. "We noticed the pits immediately upon arrival, but it took us a few weeks to realise that they were active," explains Vincent. By carefully processing high-resolution images of these cavernous depressions, Vincent and his colleagues have seen faint jets flowing from some of them at a few metres per second. "Our images have a very high range. They contain more shades of grey than our screens can display," he says. "This means that shadowed areas or dark spots in our images still contain a lot of signal. By enhancing the brightness and contrast, we can peek through the shadows and retrieve this additional information."

As 67P neared the Sun, its activity increased dramatically: more and more gas and dust was driven off the surface each day by the warmth of our star. Around the time of perihelion in August 2015, the cameras caught several spectacular cometary jets flaring from the icy nucleus. "We saw a very strong outburst in one image," says Guettler. "Fifteen minutes before, there was nothing." Guettler says the aim is now to explore how these remarkable jets form. "We have dedicated OSIRIS observations monitoring presumed active regions – regions where we have seen outbursts before. We want to see a jet being born and dying,"

THE ALLURE OF ICE

It's not just the jet activity that's fascinated the Rosetta team. The spacecraft's cameras have also spotted the distinctive glisten of ice on the nucleus of the comet. "We always knew it must be there," explains Guettler, "and when the comet slowly heated up while it was approaching the Sun, the ice evaporated and lifted the dust blanket."

With all this activity, Rosetta is getting an unprecedented view of the evolution of a comet and the processes at work on its surface. But understanding the context of this activity is vital too. It's for this reason that hundreds of astronomers around the world, using ground and space-based telescopes, have also been studying Rosetta's target.

"Understanding the large scale at the same time as we get in-situ measurements from Rosetta is key," says Colin Snodgrass, who is coordinating the observing campaign. "Ground-based data also allows direct comparison with other comets, as we have similar observations of them. In this way, it helps us use Rosetta results to interpret what we see in observations of comets more generally."

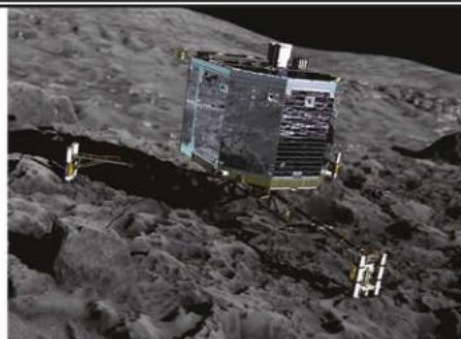
While 67P is now fading as seen from Earth, Rosetta will keep its watch around the comet until September 2016. It'll gather more data and produce ever more detailed images of the surface as it orbits closer to its cometary companion over the coming months. For project scientist Matt Taylor, it's clear there's still plenty more excitement to come.

"Basically, we've done the first half. We've had our cup of tea and a couple of orange wedges, and now we are ready for the second half," he says. "It's going to be a blinder." ■

6 August 2014

ARRIVAL AT 67P

Rosetta finally arrives 67P. The spacecraft enters orbit around the comet and mimic its trajectory as it moves further into the inner Solar System.



13 November 2014

PHILAE LANDS ON THE COMET

Philae successfully touches down on 67P, sending a huge amount of data back for 60 hours before running out of power and going into hibernation. Its subsequent communications have been sporadic.

13 August 2015

67P AT PERIHELION

The comet reaches perihelion – that is, the point in its orbit when it is closest to the Sun, a distance of 186 million km (116 million miles) away.

September 2016

MISSION ENDS?



With the Rosetta mission extended until the autumn (from its original end-date of December 2015), the 'grand-finale' is hoped to be a 'controlled impact' of the spacecraft with the comet.

IS THERE LIFE ON MOONS?

We tend to look at other planets for signs of life. But, as STUART CLARK suggests, focusing on particular moons might uncover worlds that are both habitable and inhabited



There has been an awful lot of talk recently about looking for extraterrestrial life. We are bombarded with stories about life on Mars, or about habitable worlds being found circling other stars. But could this be blinding us to the real places to look for life?

The icy moons of the outer Solar System are attracting more and more attention from planetary scientists. Decades of studies have now shown that there is a lot of liquid water locked away inside the outer moons. And if we've learnt anything from Earth, we know that anywhere you find water, you find life. Could this also be true on the outer moons?

"In terms of potential habitats, I think most astronomers are fairly sure that there are places inside many of these moons where, if you put the right kind of

organism, they would survive. So we've got habitats. We just don't know whether they are inhabited by organisms." So says David Rothery, a planetary scientist from the Open University who surveyed the moons of the Solar System for his book *Moons: A Very Short Introduction*.

Looking for life beyond Earth is no mere exercise in curiosity – it will tell us something about how life began on Earth. At present, no-one knows what conditions are right to flick the switch from mere chemistry to biology. Did this process occur readily or was it the result of a chain of unlikely events? Finding life elsewhere would help us answer this.

"If we can find places in the Solar System where life began independently from life on Earth then – wow! – that is pretty compelling evidence that if life can start, it will start," says Rothery. Life needs a power source. We once thought that the only suitable source in the Solar System was the Sun. This meant that life had to exist on a planet's surface. Hence the interest in Mars, which seems to be the most Earth-like of the other planets.

However, a discovery on the floor of the Pacific Ocean in 1977 changed all that. Researchers from California's Scripps Institute of Oceanography were exploring around the volcanic ridge known as the East Pacific Rise and found natural chimneys belching black smoke into the ocean. They nicknamed them black smokers. Known more formally as hydrothermal vents, the black smokers are where hot water percolates through the ocean bedrocks, dissolving minerals as it goes, before shooting back up into the frigid ocean water. The sudden change in temperature causes the minerals to precipitate, creating the 'smoke'. Astonishingly, there were thriving biological communities fuelled by the dissolved minerals around the vents. These were sustained not by energy from the Sun, but by the geothermal energy that had heated the water.

The discovery of oceans in some of the outer moons of the Solar System, such as Jupiter's Europa and Saturn's Enceladus, instantly raised the possibility of black smokers on those far-off moons. Perhaps most intriguingly, some of the microbes found around the black smokers were shown to be genetically the most primitive organisms on the planet. This raised the prospect that they could be the places where life began. If true, why not on the ocean floors in the outer Solar System as well?

Over the page, we name three moons where life may well be lurking...

EUROPA

Parent planet: Jupiter

Orbital period: 3.551 days

Radius: 0.245 Earth radii

Mass: 0.008 Earth mass

Planetary Habitability Index: 0.49

This was the moon that opened up our eyes to the possibility of oceans in the outer Solar System. Suspicion began in the late 1970s when NASA's Voyager 1 and 2 spacecraft passed the moon. The images showed a mostly smooth icy surface, almost devoid of craters. Since these impact scars accumulate as time goes by, for Europa to show hardly any meant that the surface was being renewed. But how?

Cracks on the surface gave the answer. In the 1990s, NASA's Galileo spacecraft explored the moon and revealed that dark material around the cracks were salty, as if they had come from an ocean. Magnetic readings also hinted at a shifting water body inside the moon. The final piece of the puzzle came in images of the surface, which clearly showed ice floes.

The heat to keep this ocean liquid was calculated to be coming from the gravity of Jupiter. A so-called tidal force that squeezed the moon, producing friction to melt the

underground ice and maybe even drive black smokers. But getting down to see them will be tough. The ice sheet that makes up the surface of Europa is estimated to be between one and 10 kilometres thick.

"It would be very difficult to go to Europa, drill through the ice and send a submersible to the black smoker on the ocean floor," says David Rothery. "But you could land at one of the cracks and sample the slush that's squeezed up through it."

This would allow specially designed equipment to look for biologically important molecules. The equipment would have to be specially designed to work in very high radiation levels. Every day, the surface of Europa is bathed in thousands of times more harmful radiation than the surface of Earth.

An astronaut standing on Europa would receive a fatal dose within 24 hours. Luckily for any life on the ocean floor, the radiation will not penetrate the ice sheets.

NASA is currently developing a mission to study the moon from orbit. Called the Europa Multiple-Flyby Mission, right now they're designing the instruments that will allow it to assess the moon for habitability. Intended for launch in 2022, the spacecraft could carry a lander built by the European Space Agency (ESA).

ESA itself has a mission to Jupiter called JUICE (JUperiter ICy Moons Explorer). Although not designed to concentrate on Europa, it will be making some flybys. During these it will use its ice-penetrating radar to measure the thickness of the ice crust.

Although Europa was the trailblazing moon for sub-surface oceans, much remains unknown because the water is mostly locked under the ice. At Enceladus, however, nature has gifted us a way of analysing the ocean just by flying past the world. This is because there are geysers jetting water from the ocean into space.

NASA's Cassini spacecraft has been targeting these plumes and flying through them so that its onboard instruments can analyse them. Various types of dust grains and chemical have been discovered in this way, including the tell-tale signature of salts. "This is pretty good evidence that we are sampling the ocean itself," says

ENCELADUS

Parent planet: Saturn

Orbital period: 0.395 days

Radius: 0.0395 Earth radii

Mass: 0.000018 Earth mass

Planetary Habitability Index: 0.35

Jonathan Lunine from Cornell University in New York.

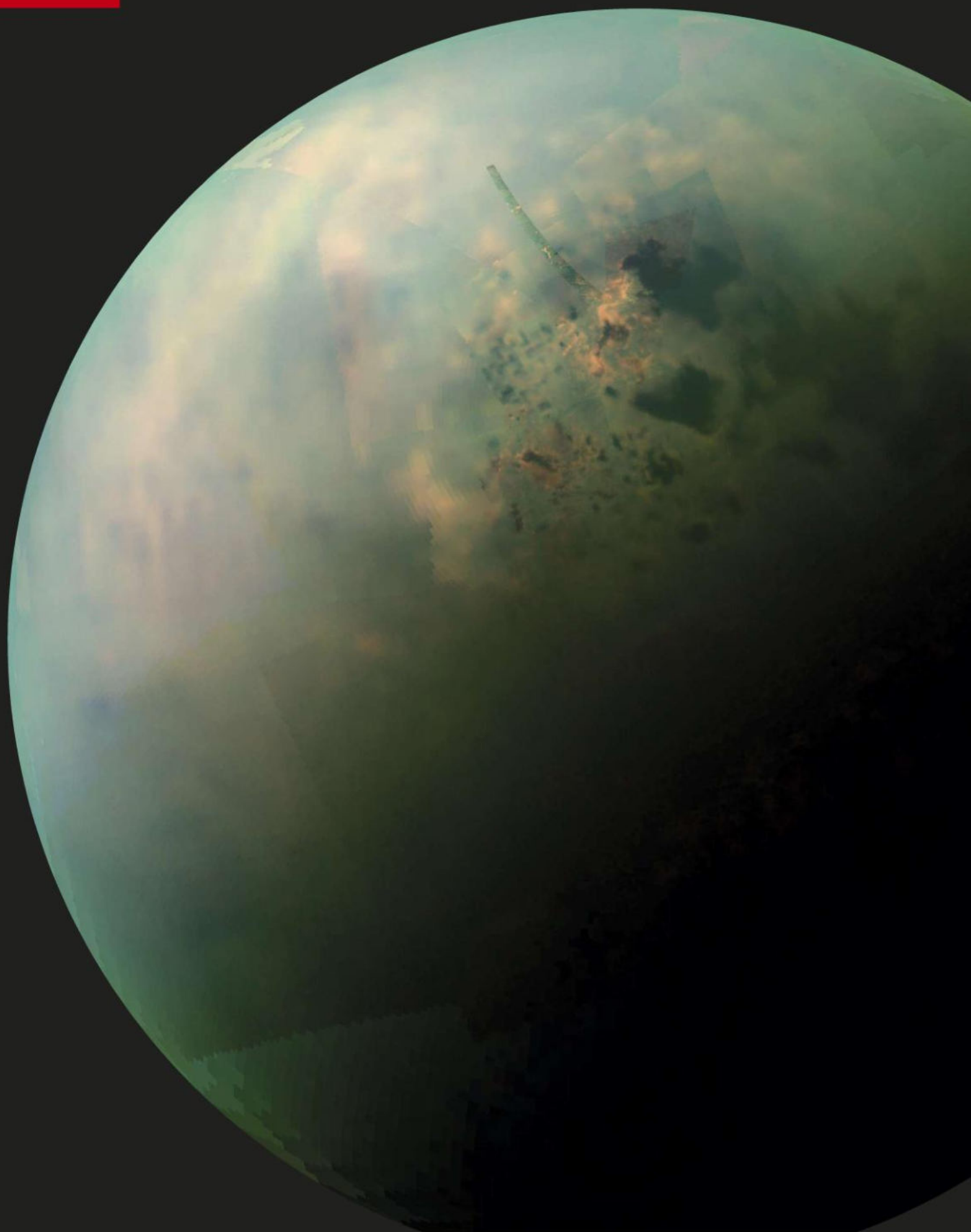
Spurred by the discovery of Enceladus' water plumes, the spacecraft operators designed a sequence of flyby that would take Cassini deeper and deeper into the plumes. "We now have an inventory of organic molecules," explains Lunine. "It is not a complete list, but it is enough to be able to say, 'Yes, we have carbon-bearing molecules inside Enceladus'." This could be crucial because, on Earth, life-giving DNA is built using carbon-bearing molecules.

On 28 October 2015, Cassini plunged to its closest flyby yet, just 48 km above the icy surface and hopefully steering through the densest part of the geysers. Planetary scientists are now eagerly analysing the results. They are on the look-out for molecules of hydrogen because if this gas is present in the water jets, the theory suggests that it must be coming from where hot water is reacting with rocks on the ocean floor.

Finding the molecule has implications for life. "Hydrogen can feed an organic pathway," says David Rothery. "A microbe could bond hydrogen onto carbon and get an energy kick out of it." This is how a form of microbe called methanogens survive on Earth. Of course, finding the chemical ingredients for such life does not guarantee that it is there. Nevertheless, this wealth of new information is edging Enceladus ahead of Europa in terms of the locations where planetary scientists think that life might be found.

"I'm inclined to boost Enceladus higher than Europa now," declares Rothery, "It is almost certainly habitable. We just don't know whether it is *inhabited*."

For now, there are no further plans to send anything back to the Saturn-Enceladus system. Once the Cassini mission ends, however, and planetary scientists start to really digest the new information, the chances are that a follow-on astrobiology-oriented mission will begin to gather support.



TITAN

Parent planet: Saturn

Orbital period: 15.945 days

Radius: 0.404 Earth radii

Mass: 0.0225 Earth mass

Planetary Habitability Index: 0.64

This moon of Saturn is an altogether more alien place. It sits under obscuring clouds that are rich in organic molecules and was revealed by ESA's Huygens lander that parachuted to the surface in 2005.

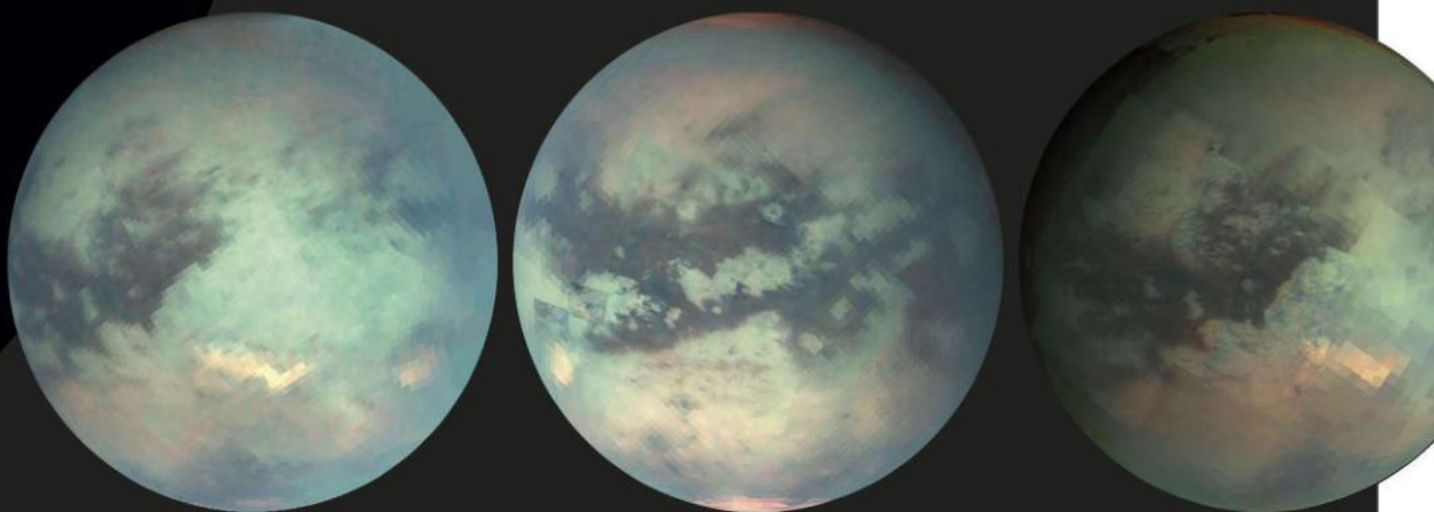
During the descent, the spacecraft made intriguing electrical measurements. Combined with measurements of the way the moon's gravitational field differs from place to place, it strongly suggests an ocean beneath the surface.

With all the organic molecules that are in the atmosphere and on the surface at Titan, there is a firm chance that the ocean would be full of them too, perhaps increasing the chances of life. But could we sample this ocean to test that hypothesis? "That's the thought question," says Jonathan Lunine. "There's nothing spewing out of that ocean onto the surface of Titan."

But maybe we don't need to go deep to discover life on this particular moon. While there is liquid on the moon's surface, it is not water. It's actually methane and ethane, and it pools in lakes and seas at the moon's polar regions. The largest is about the size of Earth's Caspian Sea. Its discovery begs an obvious question: could life be based on methane rather than water?

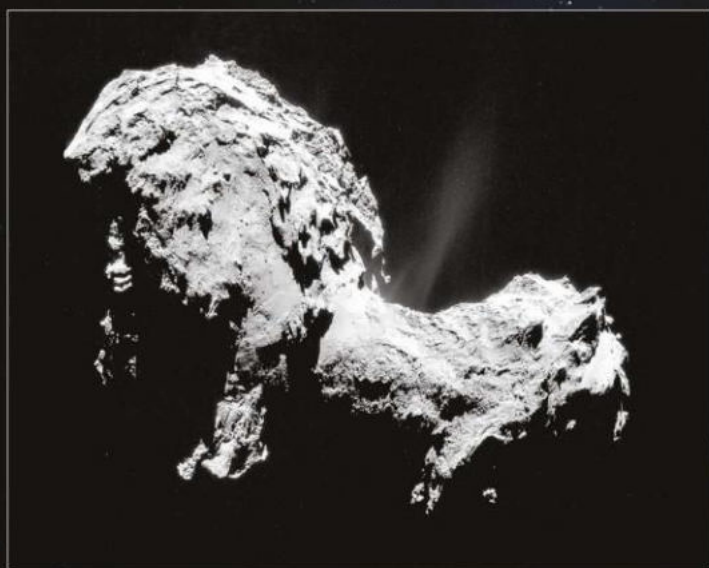
Lunine thinks it is possible. Together with some chemical engineering colleagues, he found a theoretical biochemistry that could work for methane. But testing it is going to be extremely hard.

"It's very difficult to 'cook up' biochemistry [experiments in the lab]," he notes. "It's probably just easier to go to these places and look. It would be very interesting to land on one of Titan's seas and see just what is going on there." ■



FROM COMET 67P TO THE OORT CLOUD

Our fact-filled journey across the Solar System approaches its farthest reaches...



COMET 67P CHURYUMOV-GERASIMENKO

Distance from Sun: 186,000,000km (at its closest), 849,700,000km (at its most distant)

Diameter: 4km

Composition: Analysis has revealed 16 compounds, including four never seen before on a comet. The comet also contains 'heavy water' and a lot of molecular oxygen surrounds it

Discovered: Klim Ivanovych Churyumov discovered the comet in 1969

Visits: The ESA Rosetta mission launched in 2004 to take observations and analysis of the comet. It arrived at 67P 10 years later

Fact: The comet takes nearly six-and-a-half years to travel round the Sun. Its elliptical orbit means that its distance from the Sun varies enormously



URANUS

Distance from Sun: 2.88 billion kilometres

Atmosphere: 82.5 per cent hydrogen, 15.2 per cent helium, 2.3 per cent methane

Diameter: 50,724km

Discovered: In 1781, William Herschel discovered Uranus, making it the first planet to be found using a telescope

Visits: Voyager 2 carried out a flyby of Uranus in 1986, identifying 10 new moons. We now know there are 27 in total

Fact: Uranus appears to be rotating on its side. It's thought that a collision with an Earth-sized object knocked it off its orbit

NEPTUNE

Distance from Sun: 4.5 billion kilometres

Atmosphere: 80 per cent hydrogen, 19 per cent helium, small amounts of methane

Diameter: 49,244km

Discovered: Urbain Le Verrier and John Couch Adams are given joint credit for finding Neptune in 1846

Visits: In 1989, Voyager 2 passed above Neptune, where it discovered the planet's Great Dark Spot

Fact: Neptune has 14 moons. Its largest, Triton, was found just 17 days after the planet was discovered



PLUTO

Distance from Sun: 4.4 billion kilometres (at its closest), 7.38 billion km (at its most distant)

Atmosphere: 90 per cent nitrogen, 10 per cent other molecules, including methane

Diameter: 2,372km

Discovered: Pluto was discovered in 1930 by Clyde Tombaugh. It's since been reclassified as a dwarf planet

Visits: New Horizons made its closest approach to Pluto on 14 July 2015. The craft is now travelling out into the Kuiper Belt, the region of the Solar System outside Neptune's orbit

Fact: The largest of Pluto's five moons is Charon. It orbits a common centre of gravity with Pluto and may one day be regarded a dwarf planet



Please note: the sizes of – and distances between – planets are not in proportion

HAUMEA

Distance from Sun: 6.5 billion kilometres

Atmosphere: Methane, ethane and potentially nitrogen ices

Diameter: 1,960km

Discovered: In December 2004, the dwarf planet was spotted by a team led by Caltech's Mike Brown. But this may not be the first discovery; a Spanish team claim to have seen Haumea on photographs taken in 2003

Visits: There are no specific plans to visit Haumea and its moons, Hi'aka and Namaka, but the spacecraft New Horizons may pass by one of the Kuiper Belt's dwarf planets

Fact: The dwarf planet is shaped like a rugby ball. It takes just under four hours to complete a rotation, making it one of the fastest spinning objects in the Solar System

MAKEMAKE

Distance from Sun: 6.8 billion kilometres

Atmosphere: This dwarf planet does not have an atmosphere, but its surface appears to contain methane

Diameter: 1,434km

Discovered: A team led by Mike Brown at Caltech first discovered Makemake in March 2005. It was originally known as 'Easterbunny'

Visits: There are no planned missions to study Makemake, but if a craft were to be launched, it would take 16 years to reach the dwarf planet

Fact: Makemake is about two-thirds the size of Pluto. But because it has no moons, it is particularly difficult to study

ERIS

Distance from Sun: 5.7 billion kilometres (at closest), 14 billion kilometres (most distant)

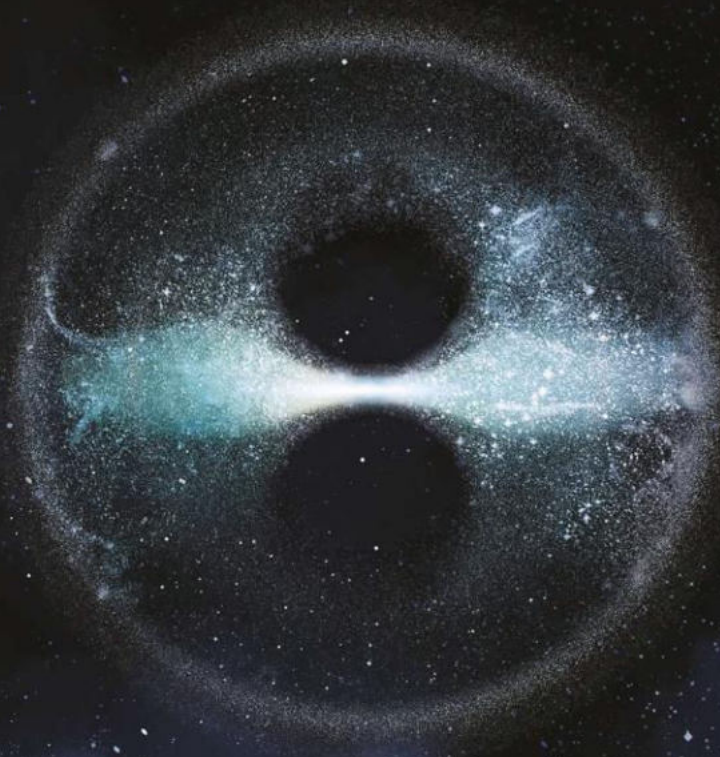
Atmosphere: Due to its distance from the Sun, Eris's atmosphere is thought to be frozen. In about 250 years, the dwarf planet will be close enough to the Sun for its ices to become gases

Diameter: 2,326km

Discovered: A Caltech team led by Mike Brown spotted the dwarf planet in 2005

Visits: There are no plans to visit Eris, or its moon Dysnomia

Fact: The discovery of Eris, which is more massive than Pluto, contributed towards the International Astronomical Union classifying Eris and Pluto as dwarf planets



OORT CLOUD

Distance from Sun: 1.6 light-years

Structure: The Oort Cloud contains trillions of objects, mostly made up of ices consisting of methane, ethane, water, carbon monoxide and hydrogen cyanide

Discovered: The theoretical cloud was proposed by the astronomers Jan Oort and Ernst Öpik in the mid-20th Century. The Hale-Bopp comet, which originated in the Oort Cloud, captured the world's attention in 1997 when it made its closest approach to Earth

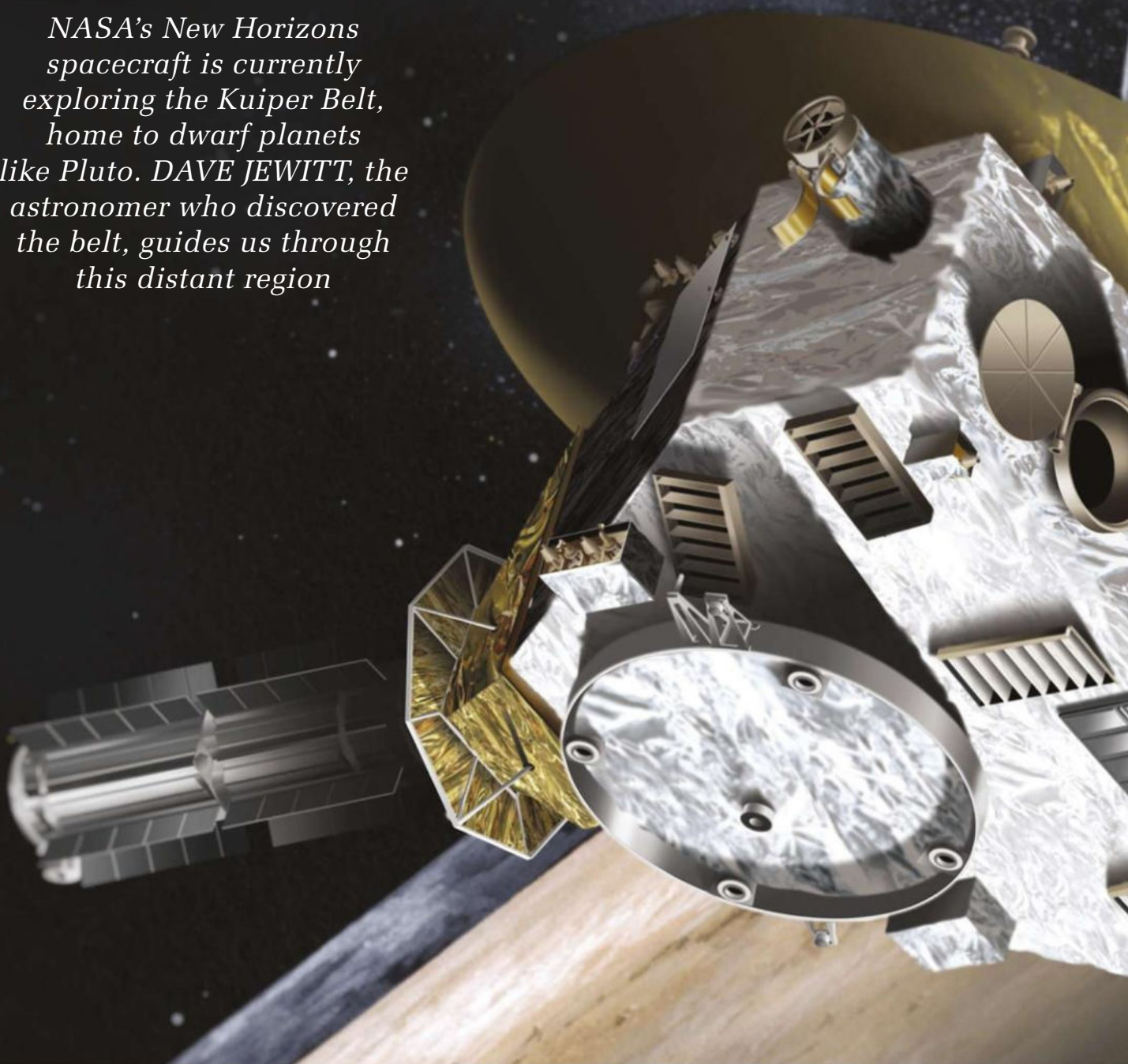
Visits: It will take 300 years for Voyager 1 to reach the Oort Cloud, but it runs out of power in 2025. As yet, there are no specific plans to visit

Fact: The Oort Cloud marks the outer edges of the Solar System, and its exterior reaches are only weakly affected by the Sun

Please note: the sizes of – and distances between – planets are not in proportion

THE FINAL FRONTIER

NASA's New Horizons spacecraft is currently exploring the Kuiper Belt, home to dwarf planets like Pluto. DAVE JEWITT, the astronomer who discovered the belt, guides us through this distant region



All of the planets out to Saturn were known to the ancients, but it's only in the past few centuries that we have been able to look farther into our own back

garden. William Herschel only discovered Uranus by chance in 1781, while Neptune's existence was later predicted on the basis of gravitational perturbations measured in the orbit of Uranus. Percival Lowell used still smaller perturbations to predict yet another planet beyond Neptune, subsequently discovered in 1930 by Clyde Tombaugh at Lowell Observatory. This was Pluto.

The 'new planet' immediately caught the attention of the world. Judging by the reaction to the current New Horizons mission, it still does. But, from a scientific perspective, things began to unravel for Pluto soon after its discovery. Unlike the ice giants Uranus and Neptune, each about 16 times Earth's mass, Pluto turned out to be an unimpressive 0.002 Earth masses – one-sixth of the mass of the Moon.

Tiny Pluto is far too small to perturb an ice giant. Even stranger, the perturbations used by Lowell to predict Pluto turned out to be just errors in the measured position of Uranus, rendering his prediction baseless. All evidence for an unseen massive body in the outer Solar System promptly evaporated, leaving only tiny Pluto, whose label as the smallest, most eccentric 'planet' gave it more importance than it deserved.

A number of scientists, including Gerard Kuiper in 1951, subsequently speculated that Pluto might not be alone. Kuiper went a step too far, though, and actually predicted that the region where we discovered the Kuiper Belt formed full but is now empty because of destabilising perturbations by Pluto. These assertions, much like those of Nostradamus, had little impact when they were made because they are too vague to be observationally tested. It was not until 1980 that Uruguayan astronomer Julio Fernández argued more convincingly that short-period comets might come from a disc-shaped region beyond Pluto, instead of from the more distant Oort Cloud as previously proposed. Even this made little stir, perhaps because of the dubious history of empty predictions made by Percival Lowell and others after him, such as Lowell's supposed observations of canals on the surface of Mars.

The simple truth is that, even for astronomers, out of sight is out of mind. Why think much about something that probably isn't even there? In the end, the Kuiper Belt was discovered not in response to any meaningful prediction but because, like Tombaugh, we were looking. Graduate student Jane Luu and I began our search in 1986, but rather than searching for a Kuiper Belt beyond Neptune, we were looking for any object beyond Saturn.

We did not succeed until August 1992, when we found 1992 QB1, the second Kuiper Belt Object (KBO) ever found. ➔



The New Horizons craft was assembled in a clean room prior to its launch aboard an Atlas V rocket

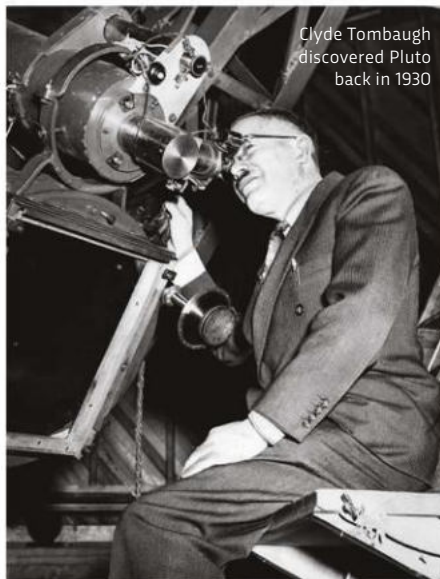
➔ Six months later, we found another object; over the next few years, the floodgates opened. We now know of around 1,600 KBOs, occupying a region vastly larger than the previously known planetary system.

AFTER THE FLOOD

So what have we learned since? Firstly, it is now clear that Pluto is a big KBO. Its peculiarly inclined, elliptical orbit suddenly makes sense – it is just like the orbits of innumerable other KBOs. Secondly, the Kuiper Belt is an enormous, deep-freeze repository holding the most primitive material in the Solar System. With temperatures only a few tens of degrees above absolute zero, even very volatile ices like carbon monoxide that cannot survive near the Sun are frozen solid in the Kuiper Belt. Icy objects leaving the belt are batted around the Solar System by the giant planets, leading to some being ejected to the interstellar medium never to be seen again, while others are captured by Jupiter. Ices in KBOs deflected near the Sun vaporise to create comets, with their familiar tails.

Thirdly, we found that while the KBOs are very numerous, their combined mass is only a modest 0.1 Earth masses. This is so small that it would be difficult for the observed objects to have accreted, even over the age of the Solar System. The solution seems to be that the Kuiper Belt started out being much more massive than it is now, perhaps containing 20 or 30 Earth masses instead of 0.1, but then lost almost all of it. Where did it go?

The answer may lie in two other observational discoveries from the 1990s. We found that the Kuiper Belt is a thick disc, more like a doughnut than a sheet of paper, showing that the belt has been unexpectedly ‘puffed up’ since it formed.



Clyde Tombaugh discovered Pluto back in 1930

And we found, much to everybody’s surprise, that the orbits of KBOs are divided into several distinct groups.

In one of these called the ‘resonant KBOs’, the orbital periods are simple variations of the 164.8 year orbital period of Neptune. For example, Pluto’s period (247.9 years) corresponds to two orbits for every three of Neptune’s. Neptune and Pluto are said to be in the ‘3:2 resonance’, along with thousands of other objects. Many other resonances (2:1, 4:3, 1:1 etc) are also occupied. But what made the Kuiper Belt so puffy, and why are there so many resonant KBOs?

ALL LINKED TOGETHER

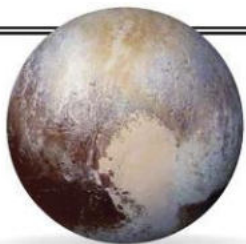
University of Arizona dynamicist Renu Malhotra gave us the answers. Resonant orbits prevent close, destabilising encounters with Neptune, allowing resonant KBOs to persist because they never tangle with ‘the big guy’. Malhotra

found resonant KBOs were trapped because Neptune’s orbit slowly expanded, from near 15 or 20 AU in the beginning to 30 AU now. As the planet scooted outwards, it trapped some of the planetesimals beyond it into resonant orbits. But the planets pull on each other by gravity so, if Neptune’s orbit changed, they all changed.

This ‘radial migration’ of the planets has revolutionised our thinking about the Solar System. In place of the old and rather boring clockwork Solar System in which the planets held their orbits and moved predictably for billions of years, we now recognise a much more chaotic, harder-to-follow history. For example, simulations show that if radial migration caused two of the major planets to fall into a resonance of their own, this would have caused the entire architecture of the Solar System to be catastrophically upset. If this happened in the past, then the initially massive Kuiper Belt would have been disrupted, showering the Solar System with debris and causing a swarm of giant impacts. All that would be left would be the puffed-up Kuiper Belt remnant that we see today.

As a result of all this, the significance of the New Horizons encounter with Pluto in July 2015 has changed since the mission was first imagined in the late 1980s. Instead of visiting the last, most peculiar planet, we find that we have visited a large but otherwise unremarkable Kuiper Belt object.

Before all this, we knew plenty about Pluto, including its mass, diameter and density, the composition of its surface ices, the nature of its atmosphere, and the properties of its satellite system. But the New Horizons encounter transformed Pluto from an astronomical object to a geological one, rich with surface detail undetectable from Earth. Hopefully, New Horizons will do it again in a few years’ time, when the spacecraft is set to pass a much smaller KBO called 2014 MU69. ■



PLUTO: PAST AND PRESENT



18 February 1930
US astronomer Clyde Tombaugh discovers Pluto on plates taken at Lowell Observatory in Flagstaff, Arizona.



24 March 1930
Pluto is named after the Roman god, following a suggestion by 11-year-old Venetia Burney from Oxford.



22 June 1978
James Christy of the US Naval Observatory discovers Pluto's large moon, Charon. It orbits the dwarf planet every 6.4 days.



May 1989
The first ideas for a space mission to Pluto are put forward by a group of 12 planetary scientists, known as the Pluto Underground.

THE NEW HORIZONS SPACECRAFT

PEPSSI

The Pluto Energetic Particle Spectrometer Science Investigation took a close look at the particles as they left Pluto.

SWAP

The solar wind that's blowing around Pluto was tracked by the SWAP device. It monitors how the wind reacts with particles escaping from the dwarf planet's atmosphere (around 75kg leave every second).

LORRI

The Long Range Reconnaissance Imager device is effectively a digital camera with a large telephoto telescope attached. This allows us to get up close with Pluto. LORRI provides the best-ever images of Pluto and the Kuiper Belt, while also looking for craters and geysers.

SDC

The Venetia Burney Student Dust Counter is the first science instrument on a NASA planetary mission that's been designed, built and flown by students. As New Horizons glides through the Solar System, it measures the concentration of dust particles throughout.

REX

This is a Radio Science Experiment that creates an 'uplink' with Earth as it passes Pluto and Charon. By monitoring the disturbance to this radio connection by the two objects, REX can tell us the masses of Pluto and Charon and other Kuiper Belt objects. The device should also be able to measure the temperatures of these bodies.

RALPH

New Horizons' 'eyes' are situated here. These consist of an array of sensors designed to map Pluto's landscape at a resolution of 250 metres per pixel. It also hunts for features such as frozen nitrogen, water and carbon monoxide.

ALICE

This UV imaging spectrometer provides the first complete picture of Pluto's atmosphere, able to tell us what gases cling to the planet and how abundant they are.



5 January 2005

Caltech's Mike Brown discovers Eris. As large as Pluto, it sparks debate about the definition of the word 'planet'.



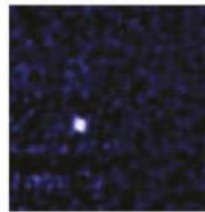
19 January 2006

Using an Atlas V rocket, NASA launches the New Horizons craft from Cape Canaveral Air Force Station in Florida.



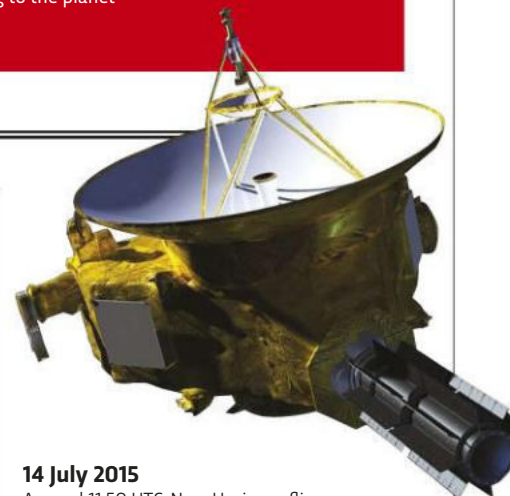
24 August 2006

In Prague, the International Astronomical Union votes to reclassify Pluto as a dwarf planet.



2011-012

Two more small satellites of Pluto – Styx and Kerberos – are discovered on photos made with the Hubble Space Telescope.



14 July 2015

Around 11:50 UTC, New Horizons flies by Pluto at a distance of some 13,700km and a relative velocity of 13.8km/s.

DESTINATION SOLAR SYSTEM

What lies under the surface of Mars? The Seven Sisters caverns could provide shelter for future astronauts, shielding them from the radiation-blasted surface

PHOTO: NASA X2

*Half a century
after Mariner 2 first
encountered Venus,
GOVERT SCHILLING
takes you on a tour to five
destinations scientists
would love to explore*

On 27 August 1962, the exploration of the Solar System commenced when NASA launched Mariner 2 – the very first space probe to travel to another planet. During its interplanetary journey, the tiny craft discovered the solar wind (the continuous flow of charged particles emanating from the Sun) and, when it flew by Venus in mid-December 1962, it revealed the planet's incredible surface temperature of 460°C. For the first time in history, mankind had physically reached out to an alien world.

Today, space exploration is no longer a novelty. Each of the eight planets in the Solar System has been studied at close quarters by spacecraft. Landers have touched down on Venus, Mars and Saturn's biggest moon, Titan. We've sampled comets, asteroids and the atmosphere of Jupiter, and it's almost impossible to keep up with the avalanche of images and data from space probes like Messenger (orbiting Mercury) and Cassini, which has been touring Saturn and its moons since 2004.

But where haven't we been? And why should we go there? On the following pages we take a trip to five unexplored places in the Solar System, from the mysterious face of Mercury, the nearest planet to the Sun, to an icy body in the outer limits. Sending missions to some of the exotic locations on the following pages will further our understanding not just of them, but also of our own planet's atmosphere and geology. Our journey of exploration has only just begun.

SEVEN SISTERS

WHAT: SUBTERRANEAN CAVERNS

LOCATION: ARSIA MONS, MARS

Underground caverns on the side of a Martian volcano could contain alien life or house future astronauts

You're way up on the slope of Arsia Mons, one of the giant shield volcanoes on Mars. Your face helmet is sandblasted by fine dust, blown across the stark landscape by strong winds. Wisps of cirrus cloud drift in the dark indigo sky. Before you is a circular hole in the ground, some 200m across. No-one knows what's inside. Would you dare to enter?

Well, scientists would love to, but might prefer to send robotic rovers in first. After all, they have no clue about the depth of the mysterious caves on Mars. They might be relatively shallow and partially collapsed lava tubes. But, then again, the dark openings could also be skylights that provide access to extensive networks of subterranean caverns.

The first Martian caves were found in 2007 by Glen Cushing of the US Geological Survey. Dubbed the Seven Sisters, they were given the nicknames Abby, Annie, Chloe, Dena, Jeanne, Nikki and Wendy. During the day, they're colder than their surroundings; at night, they're warmer – just the behaviour you'd expect for underground caves.

Over the years, more caves have been found, including one by a group of Californian middle school students. According to Natalie Cabrol of NASA's Ames Research Center, the Martian caves would be great places to explore. Why? Because their interiors are shielded from the harsh conditions at the Martian surface, which is battered by ultraviolet sunlight and cosmic rays.

The Seven Sisters might harbour extraterrestrial microbes – or at least provide a natural shelter for future human explorers.

This image from NASA's Mars Reconnaissance Orbiter shows sunlight catching the eastern wall of a Martian cavern – a pit on the slopes of the shield volcano Arsia Mons



A hotbed of science: the dark lava crust of Loki Patera



LOKI PATERA

WHAT: LAVA LAKE

LOCATION: IO, A MOON OF JUPITER

A vast lava lake on a distant moon could reveal the secrets of Earth's early geology

Located on Io, the innermost of Jupiter's four Galilean moons, Loki Patera is the Solar System's largest lava lake. Almost as big as Northern Ireland, it's usually covered with a lava crust. But every two years or so, the crust is replaced by fresh lava reaching up to 700°C.

Imagine standing on the rim of Loki Patera, looking out at an expanse of incandescent, bubbling molten rock that stretches beyond the horizon. The heat is unbearable and everything smells of sulphur. Meanwhile, the gas giant Jupiter looms above, the size of 40 full Moons in the sky. What a view! But if you're planning a visit, be very wary of lava reaching the surface. "Landing would be extremely hazardous

unless you could time the landing between resurfacing events," warns Dr John Spencer of the Southwest Research Institute in Colorado, an expert on Io.

Scientists know that Io's incredible volcanic activity is powered by giant Jupiter's tidal energy, which squeezes the rocky interior, but Loki Patera still holds many secrets. "We'd love to measure the composition of the lava, stick around long enough to see the crust being replaced, and measure the seismic activity to learn about the interior," says Spencer. In particular, he adds, studying Loki might tell scientists how volcanoes worked on the early Earth, when the heat flow was much larger – more like that of Io.

HAUMEA

WHAT: DWARF PLANET

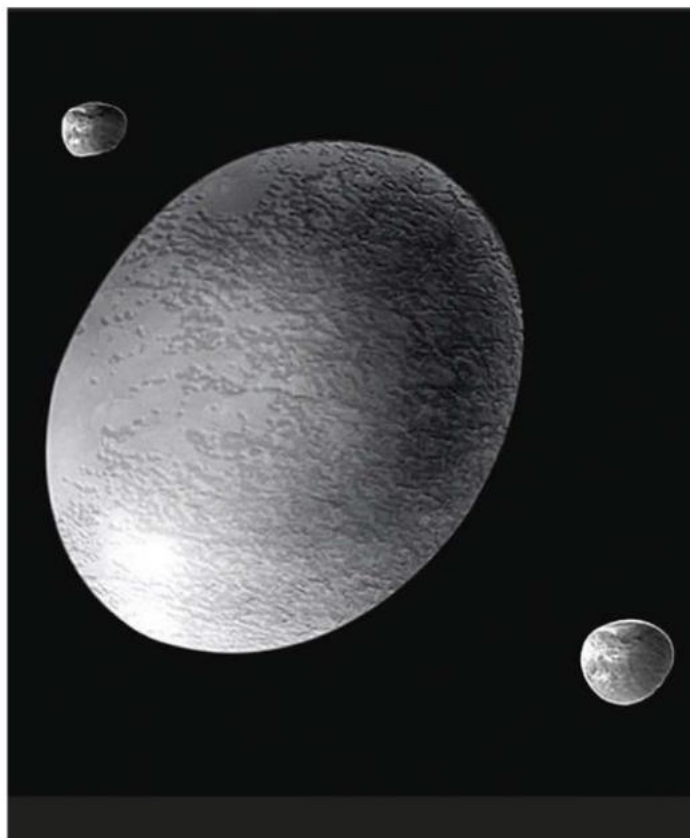
LOCATION: THE KUIPER BELT

An elongated, eccentric dwarf planet that orbits beyond Neptune

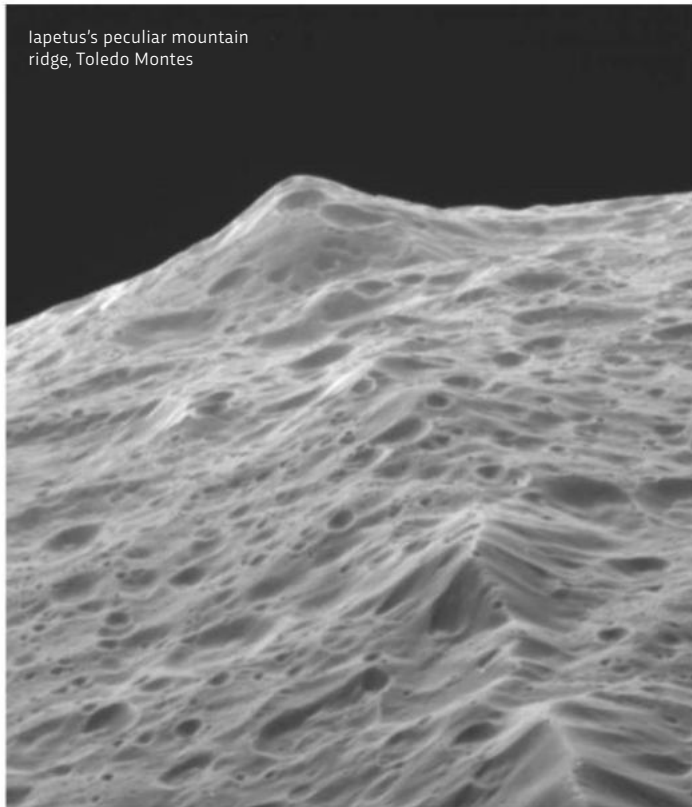
At –220°C, Haumea is one of the coldest celestial bodies in the Solar System. Twice as long as it is wide, a day on this oval rock would last less than four Earth hours. Measuring 1,960km along its longest axis – almost twice as wide as Pluto – Haumea is one of the largest inhabitants of the Kuiper Belt, a region of space beyond Neptune. The Kuiper Belt consists of asteroid-like objects, the majority of which are made up of 'ices' of methane, ammonia and water. Haumea is different in that it's composed mainly of dense rock, with a thin shell of ice and a large, reddish, mineral-rich area on its surface.

Scientists believe Haumea was much larger in the distant past, but lost most of its ice mantle layer following a giant collision in the outer Solar System. In fact, a team led by Mike Brown of the California Institute of Technology in California discovered a whole family of smaller Kuiper Belt objects that share physical and orbital properties with Haumea – most likely debris from the collision.

Haumea even has two moons: fragments of debris – named Hi'iaka and Namaka – revolve around the dwarf planet. A trip to Haumea would undoubtedly offer some fascinating insights into the violent early youth of the Solar System.



Iapetus's peculiar mountain ridge, Toledo Montes



TOLEDO MONTES

WHAT: MOUNTAIN RIDGE

LOCATION: IAPETUS, A MOON OF SATURN

How this massive mountain range formed on Saturn's moon Iapetus remains a mystery

Higher than Mount Everest, Toledo Montes is a 1,300km-long mountain ridge on Saturn's moon Iapetus. It stretches across one-third of the equator and gives Iapetus an eerie, walnut-like appearance. Some scientists think the ridge is a tectonic feature, caused by Iapetus's fast rotation in the distant past, although Dombard believes the ridge formed when a sub-satellite of Iapetus was shattered and spilled icy debris on to the surface.

Going to Iapetus would reveal the composition, age

and porosity of Toledo Montes; there might be a measurable difference in composition between the ridge and the rest of the moon. "The origin of the mountain ridge is not a solved problem by any means," says Dr Andrew Dombard of the University of Illinois in Chicago.

Given that Iapetus's surface gravity is 40 times less than Earth's, a hike to the tallest peaks of the mountain ridge would be an easy stroll, made all the more enjoyable because of the spectacular view of Saturn and its rings.

CHAO MENG-FU

WHAT: CRATER

LOCATION: MERCURY, SOUTH POLAR REGION

A colossal crater near Mercury's south pole has a permanently dark floor that's probably covered with ice

You'd be forgiven for thinking that ice on Mercury was impossible. Mercury is, after all, the innermost planet in the Solar System, with a surface cooked by the Sun to hundreds of degrees. Close to its poles, however, it's a different story. The Sun is always near the horizon, and some craters there are deep enough to have cold, permanently shadowed floors. Radar observations suggest the existence of ice in these planetary cold traps.

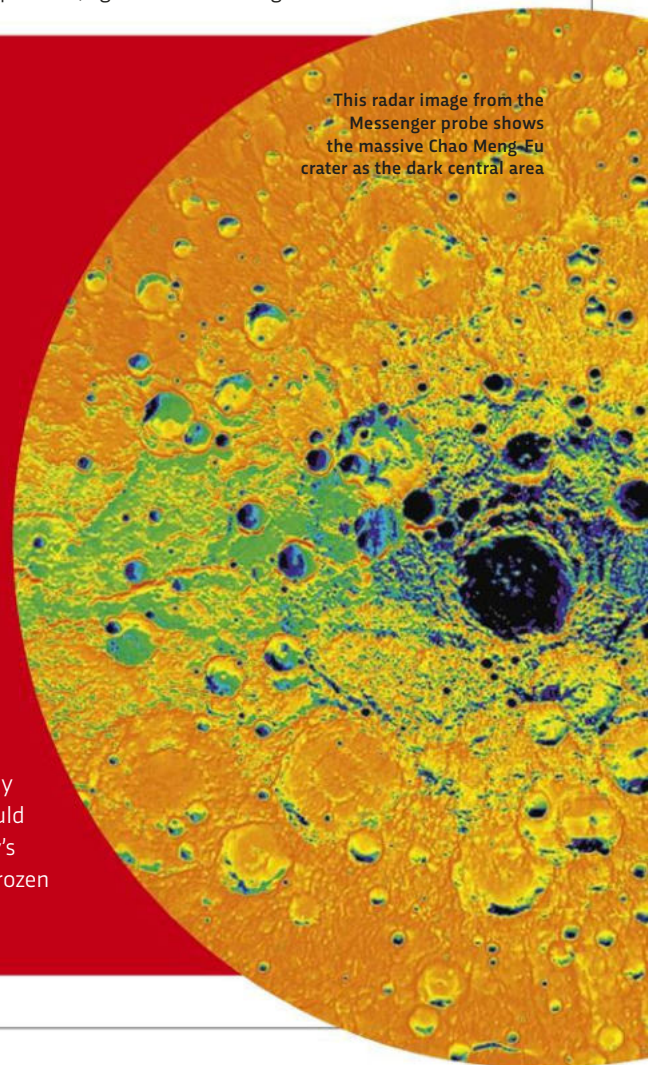
Descending into the 167km-wide crater Chao Meng-Fu – named after a 13th-Century Chinese painter and calligrapher – would be a dangerous adventure. Mercury has no atmosphere to scatter sunlight down into the crater floor, so the only light comes from the parts of the crater's rim that bask in the fiery rays of the invisible, low-altitude Sun.

These narrow, blindingly bright patches of rock would appear perched between a star-studded blackness above and an equally black but starless void below.

The crater floor is an appealing target for exploration, says Dr Nancy Chabot of the Applied Physics Laboratory at Johns Hopkins University in Maryland. "Our thermal models predict Chao Meng-Fu is cold enough to contain vast exposed ice fields. It might even be possible to go ice skating there."

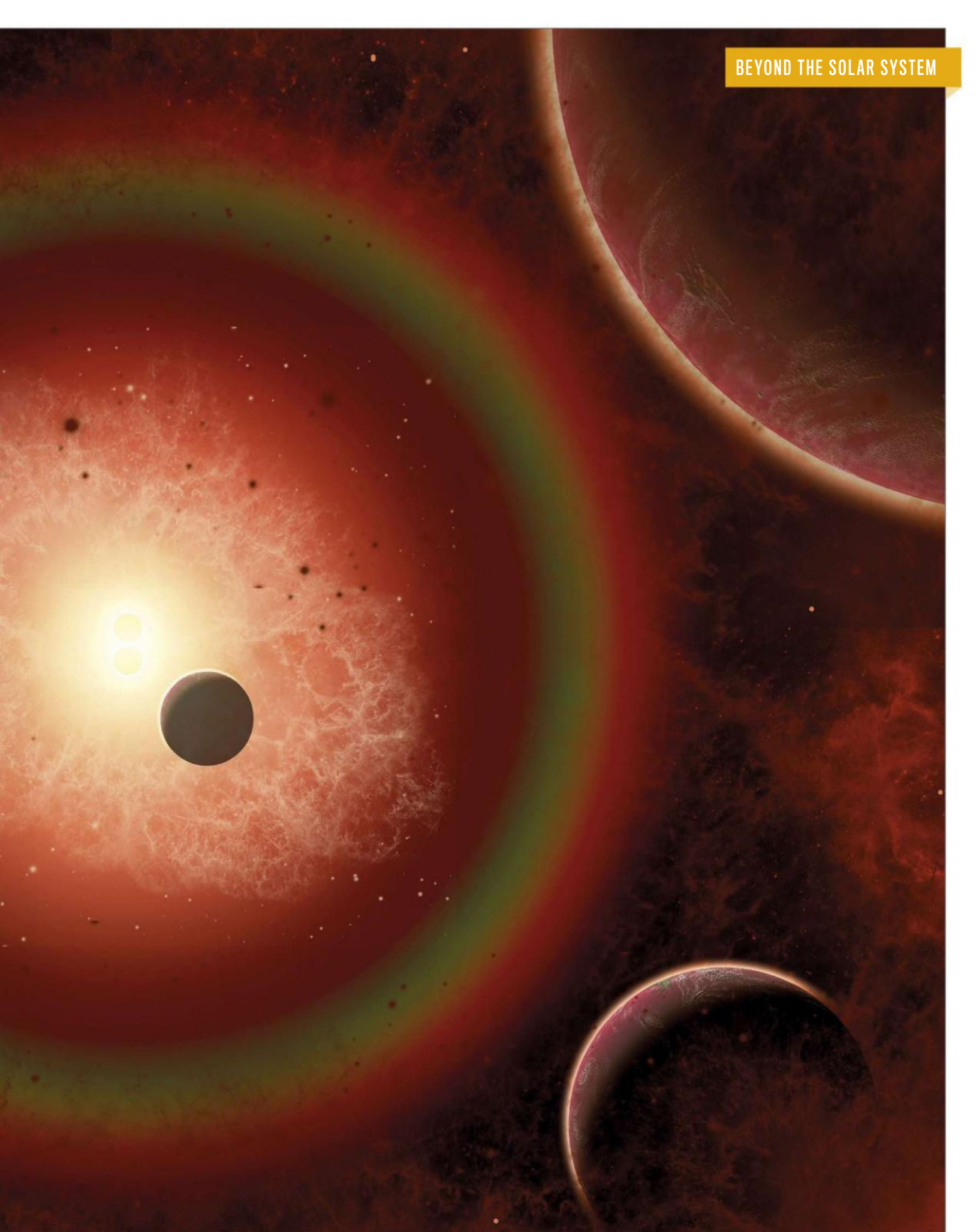
The leading hypothesis is that this ice has been delivered over the aeons by impacting comets. Ice from comets would instantly evaporate on most of Mercury's hot surface but it would remain deep-frozen on the dark polar crater floors.

This radar image from the Messenger probe shows the massive Chao Meng-Fu crater as the dark central area



BEYOND THE SOLAR SYSTEM

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THE SHAPE OF THE MILKY WAY

Ever since Galileo first spotted individual stars in the mist of light that stretches along the night sky, astronomers have been endeavouring to describe and define our Galaxy. STUART CLARK tells the story

In a dark, cloudless night, it is hard not to notice the Milky Way. At most times of the year, it stretches across the sky in a limpid band of light that invites speculation about its nature. To the Hindus, it was the great sky river, the celestial equivalent of the Ganges. To the Maori, it was the canoe of a lost traveller who scattered bright stones in the stream (the stars) so that others would not suffer his fate. To the Greeks and the Romans it was the spilt milk of a goddess, either Hera or Opis.

Beyond such flights of fancy, the story really starts in 1610, when Galileo Galilei raised his telescope to look at the luminous band of light. With no streetlights to hide it from view, it would have been a natural target for observation back in those days. Galileo's telescope had only a tiny field of view, but it was enough to see that the light of the Milky Way resolved into a plethora of individual stars.

Of course, this should not have come as a complete shock. Way back in the time of Ancient Greece, the philosophers Anaxagoras

and Democritus had both speculated that the Milky Way might be a collection of distant stars. Islamic astronomers proposed a similar theory, but it was Galileo's observations that offered up the first proof. His records mark the beginning of the scientific study of both the Milky Way and the wider Universe.

At the time, the observations raised a profound theological question about why God had made the human senses incapable of seeing all of Creation. Answering this became a driver behind the early investigation of nature. Through the invention of telescopes and microscopes that could extend the range of human senses, mankind could better understand God's handiwork.

As science progressed, it became less about the glorification of God and simply about collecting knowledge. One thing was abundantly clear about the Milky Way from the very beginning: the stars were not distributed randomly around the sky. The band of light suggested that most were concentrated into a disc.

This thinking guided philosopher Immanuel Kant, in 1755, to make an extraordinary deduction. Based upon Newton's law

gravity, which described the action of the force, and the observation that the planets of the Solar System described a band around the Sun, he suggested that the Milky Way was a vast rotating collection of stars all held together by gravity. The natural, obvious question was then to ask about the location of the Sun and planets within this rotating system.

This was where the Herschels came in. William Herschel lived with his sister, Caroline, and together their hobby was astronomy. His life changed completely on 13 March 1781 when he discovered the seventh planet Uranus. Four years later, he began a series of star counts. He assumed that stars were more or less evenly distributed throughout the disc of the Milky Way, and that by counting them in all directions he could work out where we are in relation to the centre.

It was not terribly successful because no-one then knew that the Milky Way is full of dust, which absorbs the light from more distant stars, rendering them invisible. This made it seem as if there were more or less the same number of stars in every direction. Herschel then concluded that the Milky Way must be like a 'grindstone'; a flat disc of stars more or less centred on the Sun.

Although wrong, this was effectively the line of thinking even into the 20th Century, when Dutch astronomer Jacobus Kapteyn tried the same method with contemporary telescopes. He devoted time to this project on and off for his whole life, finally publishing his masterwork in 1922 under the name: *First Attempt At A Theory Of The Arrangement And Motion Of The Sidereal System*. He concluded that the Milky Way was about 40,000 light-years across, but the dust problem led him to place us very close to the centre of the Galaxy.

In fact, by this time, the correct location of our Solar System had been computed by Harlow Shapley, an astronomer from Nashville, Missouri who went on to become the Director of Harvard Observatory, Massachusetts. The year was 1920 and, instead of stars,



IN A NUTSHELL

How do you study the shape and size of something when you're inside it? It was a conundrum faced by astronomers over hundreds of years as they sought to understand our place in the Galaxy and the wider Universe.

TIMELINE

It's taken centuries of stargazing to arrive at our current understanding of the structure of the Milky Way



Galileo Galilei raises his telescope to the sky and discovers that the band of light known as the Milky Way is actually a vast collection of individual stars.

1610

1755

Immanuel Kant suggests that the Milky Way is a rotating system of stars all held together by gravity. This is only proved beyond doubt in 1927 by Jan Oort.



William Herschel and his sister Caroline begin to count the number of stars in particular directions across the night sky, hoping this will betray the shape of the Milky Way.

1785

1920

Harlow Shapley studies the distribution of globular star clusters across the night sky and finds them clustering in the south. This shows that the Sun is located far from the galactic centre.



1927

1951



Jan Oort continues the work of his supervisor, Jacobus Kapteyn, in studying the motion of stars. He shows that they follow a systematic pattern, proving that the Milky Way is rotating.

William Morgan presents a study of the brightest stars in the Milky Way, showing that their distribution across the night sky is strong evidence for our Galaxy having spiral arms.



➔ he counted globular clusters. These are spherical collections of stars that can be seen all over the sky. Shapley reasoned that they would be in orbit around the centre of the Galaxy and that, if the Solar System were in the centre of the Milky Way, the globular clusters would be dotted evenly around us too.

Instead, he found that most were located in the southern sky, around the constellation of Sagittarius, where the Milky Way made a distinctive bulge in the sky. Shapley concluded that this was the direction of the Galactic centre and set about calculating the distances of the globular clusters using the brightness of pulsating variable stars as his yardstick.

He concluded that the Sun is located about three-fifths of the way from the centre of the Galaxy to its edge. This is indeed the location of the Sun, but Shapley significantly overestimated the absolute distances because, like those who came before him, he did not understand that there was obscuring dust in the Milky Way. He mistook the dimming effects of the dust as being down to distance, and so arrived at a figure for the Sun's distance from the centre of the Galaxy as 90,000 light-years. We now know that the correct distance is about 27,000 light-years.

SPIRALS IN SPACE

The next piece of evidence to slot into place about the shape of the Milky Way was its spiral structure. By the time Shapley was at work, evidence was mounting that the disc may be shot through with a spiral pattern of stars.

Back in the middle of the 19th Century, William Parsons, the 3rd Earl of Rosse, had built the Leviathan telescope. This gigantic telescope was 1.8m across and higher than a house. It was constructed at Birr Castle in County Offaly in Ireland. Using it, Rosse could see spiral structures in some of the nebulae scattered across the sky. Could the same be true for the Milky Way?

By Shapley's time, there was a debate among astronomers about whether the spiral nebulae were distant galaxies or nearby gas clouds. This was resolved in 1925 when the American astronomer Edwin Hubble identified variable stars in some of the spiral nebulae and calculated their distances. This showed that they were much further than the confines of the Milky Way that Shapley had worked out. The spiral nebulae had to be distant galaxies, full of their own collections of stars.

Thus, astronomers began to strongly suspect that the Milky Way too must

JARGON BUSTER

Understand the Milky Way with these key terms

1 GALAXY

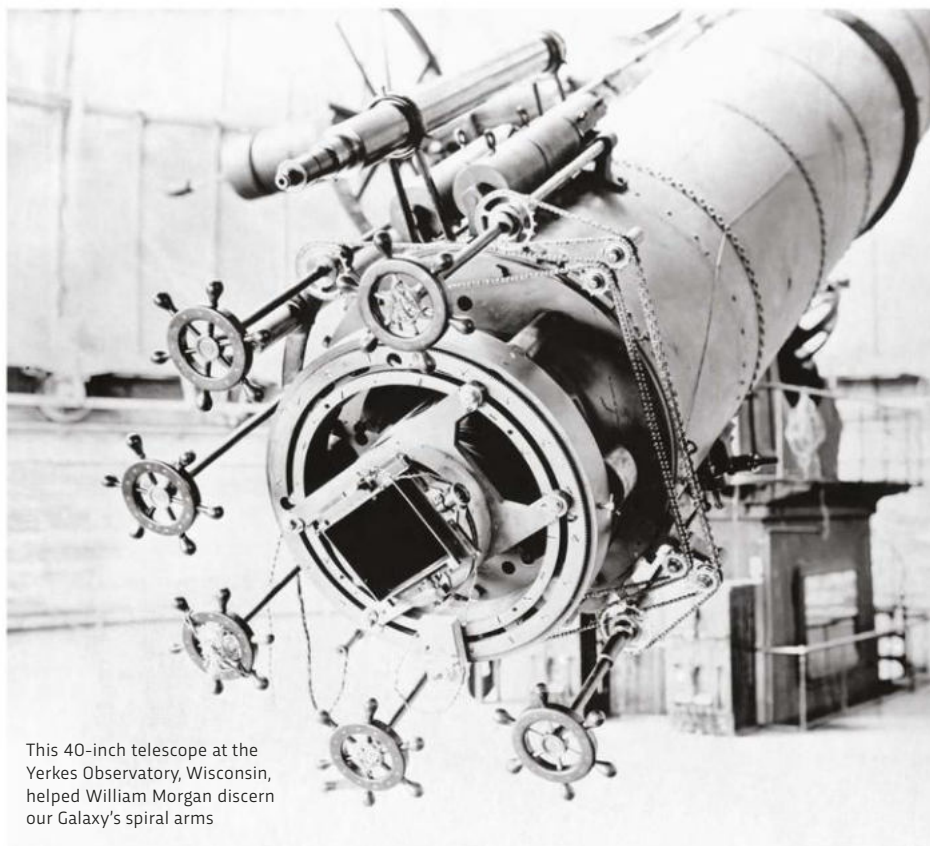
A galaxy is a collection of many millions or billions of stars. The nature of galaxies was recognised by Edwin Hubble in the 1920s. He classified them according to their shape, showing that many of them are spirals.

2 THE MILKY WAY

Traditionally this is the name for the misty band of light that stretches across the night sky. This is now known to be the plane of our Galaxy, and the name is used to describe our Galaxy and its 200 billion stars.

3 NEBULAE

From the Latin word for cloud, nebulae is the term used for clouds of dust and gas in space. Originally used for galaxies too, this usage became increasingly anachronistic after Hubble showed galaxies to be distant collections of stars.



This 40-inch telescope at the Yerkes Observatory, Wisconsin, helped William Morgan discern our Galaxy's spiral arms

be a spiral. But how could this be proven? It was completely impossible for astronomers to magically launch themselves out of the plane of the Galaxy to look down on it from above – the distances were simply too great.

Dutch astronomers, inspired by their great doyen Kapteyn, tried again to count stars. They reasoned that if there was a spiral structure to the Galaxy, then the density of the stars in the vicinity of a spiral arm would increase. They counted and they counted – and they got nowhere. Indeed, one of this method's practitioners became so disillusioned that he claimed in the 1930s that the problem of the Milky Way's structure would likely remain unsolved during his lifetime.

Astronomers needed a different way to attack the problem. In the United States, William Morgan focused on just the brightest stars. These are the blue supergiant stars and are much less numerous than the run-of-the-mill yellow and red stars. Morgan traced them out across the sky, showing that the pattern suggested three spiral arms. He called these the Perseus, Orion and Sagittarius arms. Before he could capitalise upon his discovery, however, ill health led to

him being hospitalised and astronomer Jan Oort from the University of Leiden in the Netherlands stole a march using radio telescopes.

GALACTIC RADIO

Unlike visible light, radio waves aren't troubled by the interstellar dust and so can be seen across large tracts of the Galaxy. Radio telescopes can be tuned to isolate single frequencies and so pinpoint the radio waves coming from specific molecules or atoms. In particular, Oort and colleagues targeted the 21cm waves that are spontaneously emitted by hydrogen atoms.

They mapped out giant clouds of gas across the Galaxy that also appeared to show a spiral shape. Whereas Morgan could only see the nearby structure, Oort and colleagues could see across most of the Galaxy. They interpreted their data to mean that four arms of stars wrapped themselves around the Milky Way. These arms were termed Norma, Scutum-Centaurus, Perseus and Sagittarius. In this view of things, Morgans's Orion arm is just a spur that runs from the Perseus to the Sagittarius arm, rather than a complete arm in its own right.

In recent years, however, the four-arm model has been subject to strong



ESA's Gaia spacecraft is launched from French Guiana late last year to map the position and motion of a billion stars in the Milky Way to make a three-dimensional map of our Galaxy

One thing is now clear. The Galaxy's centre is a bulge of older stars, located in the direction of the constellation of Sagittarius

challenges. Some astronomers believe that there are just two major arms, and that the rest is composed of spurs and arcs of stars. Spiral galaxies composed of many bits of arms are known as 'flocculent spirals', whereas those with a few, well-defined arms are termed 'grand design'.

The European Space Agency's star-mapping Gaia spacecraft will add data to this debate. Launched in December 2013, it is currently busy conducting a survey of one billion stars in the Milky Way. It will record precise positions, distances and movements of these stars, which will give more details about how the Milky Way is structured.

Radio telescopes on Earth are also being used in another way to tackle this problem. They are targeting specific gas clouds across the Galaxy that happen to emit microwaves in the same way that a laser works. These naturally occurring microwave lasers are known as MASERS and their distances can be measured with great accuracy.

Following their motion over a period of time reveals the movement of our Solar System and so allows the distances to the spiral arms to be calculated more accurately. This refinement will allow the structure to be seen more easily.

While questions remain about the number of spiral arms, one thing now

does seem clear. The centre of the Galaxy is a bulge of older stars, located in the direction of the constellation of Sagittarius. The central bulge is elongated into a bar of stars some 3,000-16,000 light-years in length, from which the spiral arms (however many of them there really are) begin.

The centre of the Galaxy is home to a supermassive black hole containing approximately four million times the mass of the Sun. This has grown during the 10-billion-year history of our Galaxy and continues to grow today.

The latest twist took place in 2010, when two gigantic bubbles of particles were discovered by NASA's Fermi Space Telescope because of the gamma-rays they were emitting. One is above the centre of the Galaxy, the other is below. They may be driven by star formation taking place around the Galaxy but no-one knows for certain.

The Milky Way continues to be a fascinating, mysterious place. While we certainly know a lot more about its shape than we once did, the details continue to elude us. ■

UNDERSTAND THE LIFE CYCLE OF A STAR IN 10 MINUTES

What are they? What are they made from? And how long do they live? BRIAN CLEGG offers the beginners' guide to the not-so-humble star

HOW ARE STARS BORN?

Looking into the night sky, it might seem that most of space is empty, but the gaps between the stars contain molecules of gas, the majority of which are the lightest element – hydrogen. These molecules can drift around indefinitely, but some areas have a greater amount of gas than others. Where these ‘molecular clouds’ are particularly dense, there can be enough gravitational attraction to pull the gas molecules together in a clump. This can happen as a result of random motion, but is sometimes triggered by nearby events – for example, the shock wave from the explosion that sometimes occurs as the final gasp of a star, which can push molecules together so that the death of one star seeds the birth of another.

As the gas molecules are crammed together tighter and tighter by gravity, they heat up, just as a bicycle pump gets warm when you compress the air in it. But in the star, the scale of this compression is so great that it can transform a dense ball of plasma into a nuclear reactor emitting vast quantities of energy.

WHAT EXACTLY IS A STAR?

A massive ball of plasma, the fourth state of matter on top of the familiar solid, liquid and gas. A plasma like that in a star is the result of heating a gas so much that its atoms lose electrons, producing a mix of positively charged ‘ions’ and free electrons. The sheer amount of matter in a star is phenomenal. The Sun, for instance – our neighbourhood star – contains more than 99 per cent of the mass of the Solar System. It’s more than 300,000 times the mass of Earth.

WHERE DOES A STAR’S POWER COME FROM?

As the gas that formed the star gradually comes together, it gets hot enough to form a plasma, which starts to glow – albeit very faintly compared with the vast energy output of a star. As the material continues to condense – a process that will take hundreds of thousands of years – the temperature and pressure get higher and higher. In the heart of a star like the Sun, the temperature can easily reach as high as 10,000,000°C. Under these conditions, a process called nuclear fusion can take place.

In fusion, light elements are combined to form heavier ones. The typical star reaction builds a more complex nucleus from hydrogen nuclei (the ions left when an electron is stripped off a hydrogen atom), forming the next heaviest element – helium. When the

ions get very close together, a force that pulls them towards each other, called the strong force, overwhelms the electrical repulsion between their positive charges. However, even in the heat and pressure of the core of a star, the ions aren’t squashed close enough for the very short range strong force to take hold. The star also relies on a weird quantum effect called tunnelling, which means that quantum particles like ions can pass through a repulsive barrier as if it were not there, getting the ions close enough to fuse. This process produces a flow of energy in a nuclear fusion reaction – the same source of energy used to devastating effect in a hydrogen bomb.

Some of this energy is given off as heat, and some as light, so photons of light start to find their way out of the vast ball of the star. But

it’s very easy for the photons to be absorbed by another part of the plasma, then reemitted later – so in practice it can take millions of years for light emitted near the heart of a star to emerge. Because of the stellar scale, the energy output is vast. The Sun, for instance, puts out around 400 billion, billion megawatts, of which around 89 billion megawatts hits the Earth. Though it’s only a minute fraction of the solar output, it’s thousands of times the energy that humans currently use.



WHAT WE STILL DON'T KNOW ABOUT STARS

These key terms will help you understand the Universe

WHAT CONDITIONS MADE STAR FORMATION POSSIBLE?

Initially, the Universe was too energetic for stars to form. But as the Universe expanded and cooled, it became possible for gravity to form clumps of gas. There's a suggestion from the European Planck satellite that conditions made it possible for stars to form within 500,000 years of the Big Bang, but there is uncertainty about these early years. Both space telescopes and cosmic microwave background detectors will help us discover more about the early Universe.

THE MECHANICS OF SUPERNOVAS

Although there are theories on how supernovas work, there's not enough evidence to be sure that these theories are correct. As an example, neutron stars often leave a supernova explosion at high speed, but no-one knows why the explosion should favour one direction only. Some of the most useful supernova observations come from X-ray and gamma ray space telescopes like Chandra and NuSTAR, which constantly add data that may help us understand these massive stellar explosions.

ARE THERE POPULATION III STARS?

Stars are classified either as Population I (metal-rich) or Population II (metal-poor). The older Population II stars contain fewer heavy elements, because the young Population I stars gain heavy elements from supernovas. However, cosmological models suggest that there should also be huge, ancient Population III stars, made almost entirely from hydrogen and helium, and created soon after the Big Bang. These are yet to be detected, but the James Webb Space Telescope – launching in 2018 – could change all that.

IS THE SUN A TYPICAL STAR?

The Sun looks very different to the tiny points of light that stars appear to be, but that's just a matter of distance. The nearest star after the Sun, Proxima Centauri, is around 250,000 times further away. Although all stars visible with the naked eye look pretty much the same, there are variations in colour and brightness – and the actual range of stars is much greater because the stars we see are widely varying distances away. In the

confusing terminology of astronomers, the Sun is a yellow dwarf star – it's not yellow, nor is it particularly small. The Sun is actually white – it just appears yellow because the bluer parts of its light are scattered by the atmosphere, producing our blue sky. And the term 'dwarf' is used to contrast stars like the Sun with huge stars, known as giants. In reality, the Sun is in the top 10 per cent of stars in our Galaxy for brightness.

WHAT WILL HAPPEN WHEN THE SUN RUNS OUT OF HYDROGEN?

As a star like the Sun converts its hydrogen into helium, it becomes hotter. This is because the helium takes up less room, allowing the core of the Sun to contract and generate more heat. This moves the star up the main sequence. The Sun has been in existence for around 4.5 billion years, during which its brightness has already increased by about 30 per cent, and it will spend 10 billion years on the main sequence altogether. We probably have another two to three billion years before the Sun gets so hot that the Earth becomes uninhabitable. When the vast majority of the hydrogen in the core has been used up, a star can no longer stay on the main sequence. Like similar stars, the Sun is expected to become a red giant (typically an orange colour), ending up perhaps 200 times bigger than it is now. This happens because the core, lacking hydrogen reactions to fluff it up, collapses, generating a lot of energy which pushes away the outer parts of the star. The star is still powered by hydrogen fusion, but now it is spread over a wider shell, meaning that the surface temperature of the star drops, producing the redder colour. The Sun is expected to remain a red giant for around a billion years.



AND THEN WHAT?

When most of the hydrogen is exhausted, the Sun will reach a point where helium fusion can take place. In a rapid process known as the helium flash, around a tenth of its helium will be converted into carbon. (Although it's called a flash because there will be a huge energy release, it won't be visible, as the light will not get out of the Sun.) For the next 100 million years or so, the Sun will burn through the rest of its helium, followed by a series of pulses as the core collapses again, leading to a point where it has entirely blown off most of its outer layers. Those layers form a glowing cloud of gas called a planetary nebula around the remainder of the star. It should be no surprise by now that this name is misleading – when first observed around other stars, such clouds were thought to be caused by planets. The core of the Sun that remains will be much hotter than its earlier surface, forming a miniature white star – perhaps similar in size to the Earth – at the centre of the nebula, called a white dwarf. By this stage, there is no more fusion occurring, so the star very gradually fades over billions of years. It's expected eventually to become a black dwarf, giving off hardly any light, but none of these exist yet because the Universe has not been here long enough for them to form.

THE LIFE CYCLE OF A STAR



JARGON BUSTER

CORE

The heart of a star. With extremely high temperature and pressure, this is where most nuclear fusion occurs.



ION

An atom that has lost (or gained) electrons so that it is electrically charged. Stars are made up of ions.



NEBULA

A fuzzy object in the sky, from the Latin for cloud. Originally used for anything spread out, including galaxies, but now only a cloud of gas or dust.



QUANTUM TUNNELLING

The particles that make up matter and light behave very differently from familiar objects. Such particles do not have a specific location, making it possible for them to appear on the other side of a barrier without passing through it. This is quantum tunnelling.



STANDARD CANDLE

Stars or supernovas with a known brightness are often used to measure distances in space, as the further away they are, the dimmer they will seem.



STRONG FORCE

One of the four fundamental forces of nature, the strong force is responsible for the attraction between nuclear particles. The strong force is extremely short range – particles have to get very close to each other before it has a noticeable effect.

WHAT HAPPENS TO STARS THAT ARE BIGGER THAN THE SUN?

The very bright O main sequence stars, and the most massive B stars, take a very different path to the Sun as they evolve. These stars, ten or more times the mass of the Sun, have very short lives, ranging from hundreds of thousands to tens of millions of years. Because of their extra gravitational pull, they burn through their core hydrogen quicker and

expand to form red supergiant stars. In these, helium begins to fuse once the core hydrogen has gone, followed by further fusion reactions. These produce not only carbon but also the heavier elements all the way up to iron – the end of the road for fusion produced by gravity. When the iron core collapses, the outcome is a massive explosion called a supernova.

CAN WE DETECT SUPERNOVAS ON EARTH?

Supernovas produce immense bursts of light. This means that a star that is usually much too far away to be seen suddenly becomes visible. What seems to be a new star appears in the sky – these were originally named 'nova' as a contraction of 'stella nova', the Latin for 'new star'. (The naming system later changed, making a nova a special kind of star explosion where a white dwarf sucks in material from a nearby star, so the original nova was renamed a supernova.) Supernovas can

be so bright that they are briefly visible in the daytime. As the supernova subsides, the result is a vast glowing skein of stellar debris called a nebula. Probably the best known is the Crab Nebula, which is the remainder of a supernova seen on Earth in 1054. With modern telescopes, we can detect supernovas in galaxies outside the Milky Way and, because particular types of supernova have similar brightness, they are used as 'standard candles' to measure the distance to faraway galaxies.



CAN WE SEE ALL THE DIFFERENT STAGES OF STAR IN THE NIGHT SKY?

Most star types can be observed, with the exception of black dwarfs. Dwarfs of all varieties are by far the most common stars in the Galaxy, but there are also red giants, like Aldebaran, located in the constellation of Taurus, and supergiants, like Rigel, the bottom-right star in the constellation of Orion.

Neutron stars and black holes can't be seen directly, but we can observe their effects. Neutron stars, for instance, usually rotate rapidly and give off lighthouse-like beams, which we see as flashing sources known as pulsars. And the existence of black holes can be deduced from their impact on matter around them, which gives off radiation as it plunges towards the collapsed star. Most difficult to spot are brown dwarfs, which fall between a gas giant planet like Jupiter and a star. They aren't massive enough for hydrogen fusion to be triggered, so they glow faintly as a result of the heating caused by contraction. Essentially, they're failed stars.

WHAT HAPPENS AFTER A SUPERNOVA?

During a supernova, the outer parts of the star are blasted off by a pressure wave so intense that heavier atoms than iron, such as copper and gold, can be formed. The inner remnant of the star continues to collapse and, depending on its size, will form either a neutron star

– an immensely dense star composed solely of neutron particles – or a black hole, where the collapse has become unstoppable and the star ends up as a dimensionless point with a gravitational pull so strong that not even light cannot escape.



NOW EXPLAIN IT TO A FRIEND

A STAR IS BORN

Stars are formed when clouds of gas are pulled together by gravity. As the gas particles are squeezed closer and closer together, they warm up. Eventually they are pressed together so closely that they begin to join up, giving off energy in nuclear fusion: the cloud has become a star.

STARS ARE RESTLESS OBJECTS

Not all stars are the same: they differ in size, brightness and colour. What's more, they evolve over time. Most stars will get brighter

as they move through their life cycle, until they run out of fuel in their core, at which point many of them fluff up to produce a huge 'giant' star.

EVERYTHING MUST END

The giant phase does not last forever. A mid-sized star that became a giant is likely to blow off its outer layer as a cloud of gas, leaving a small, white dwarf behind. Larger supergiants undergo cataclysmic explosions called supernovas, generating heavy elements and leaving a neutron star or black hole.

IN A NUTSHELL

Stars don't stay the same: they evolve, getting hotter before fluffing up and either shedding an outer layer or exploding as a supernova.



THE EXISTENCE OF BLACK HOLES

The idea of 'dark stars' that gobble up any planets in their path dates back to the 18th Century. But, as BRIAN CLEGG explains, it wasn't until 1964 that hard evidence of their existence emerged

Computer rendering of a supermassive black hole. Jets of matter are emitted at right angles to the accretion disc

Black holes have escaped from astrophysics into the everyday imagination. Yet the gaps in our knowledge of their nature and even, possibly, their existence are considerable.

Black holes were born from theory, not observation. We have known about conventional stars for as long as we've been able to look up at a clear night sky. But no-one ever saw a black hole. Instead, they were predicted to exist at a time when there was no way of checking whether there was really any such thing out there. And that prediction happened not once, but twice.

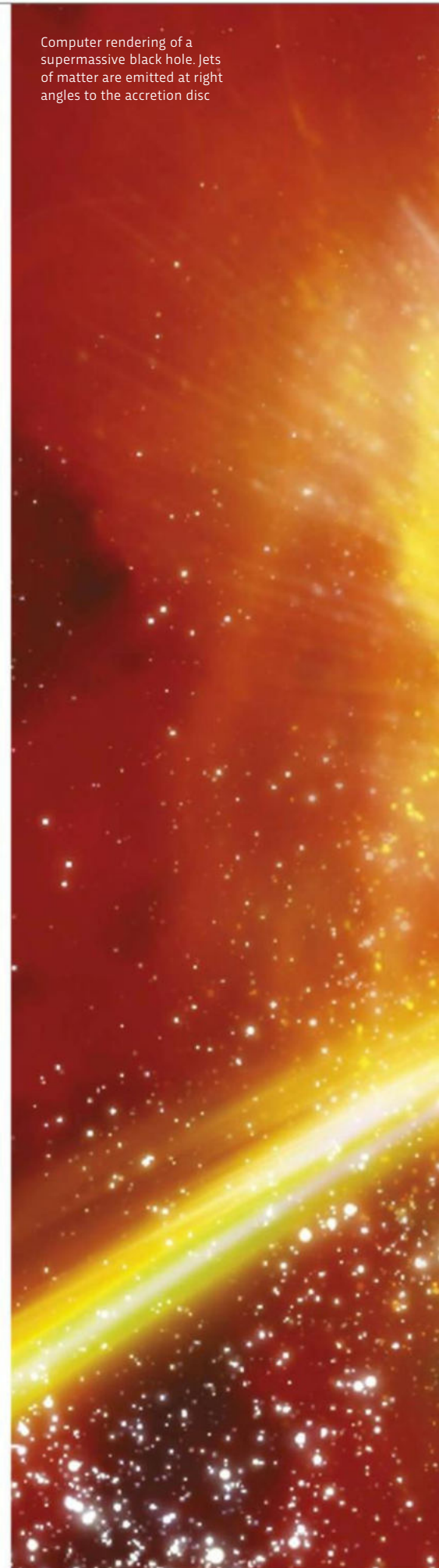
The first inspired thinking on the matter was back in the 18th Century. The man who dreamed up what he called 'dark stars' was John Michell, a Cambridge scientist who later became a clergyman. It was from his rectory that he came up with the concept, combining two key ideas of the latest science at the time.

One was escape velocity. Michell knew that when a bullet is shot straight up into the air, it has just two forces acting on it once it leaves the gun – air resistance

and gravity. As it gets higher, both of these forces weaken. The air gets thinner and, as Newton had made clear, gravity's attraction drops off with the square of the distance between the centres of the bodies involved – in this case, the bullet and the Earth.



Ole Rømer calculated a speed for light, settling the dispute over whether it travelled instantly, or just very quickly



IN A NUTSHELL

Studying black holes is particularly difficult as they cannot be seen directly. The work of eminent scientists like Albert Einstein, Kip Thorne and Stephen Hawking has helped increase our understanding, but many gaps in our knowledge still remain to this day.

→ A typical bullet from the black powder guns of Michell's day could travel as fast as 300 metres per second. But despite this impressive velocity, the forces acting to slow it brought the bullet back down to Earth. Michell, though, knew that a bullet travelling about 37 times faster would be able to overcome the Earth's attraction and fly off into space. It would have achieved escape velocity. He combined this idea with a discovery from the 1670s, when Danish astronomer Ole Rømer realised that an apparent variation in the timing of Jupiter's moons was

caused by the varying time that light took to reach us from the planet.

LIGHT CONVERSATION

Ever since ancient times, there had been arguments over whether light travelled instantly, or just extremely quickly. Rømer found evidence for a measurable speed, as the changing relative positions of Jupiter and Earth in their orbits varied the time that light took to reach us. He calculated the speed of light to be around 220,000km/s.

In the following 100 years, this figure was measured more accurately so that Michell was working with something closer to our current 300,000km/s. But the specific value didn't matter – the point was that light had a speed.

Combining the two concepts of escape velocity and light having a finite speed, Michell wondered what would happen if a massive star had an escape velocity that was above the speed of light. The more mass in a body, the higher its escape velocity. Therefore, in principle, there could be a star so vast that even light

THE KEY EXPERIMENT

Black holes are tricky to study as even the closest one lies many light-years away, but scientists can identify candidates by observing their X-ray emissions

Performing experiments on black holes is a non-starter, as the nearest candidate so far detected is around 3,000 light-years away.

Official confirmation of Cygnus X-1, the first significant candidate found, took a number of years as no single observation was capable of establishing such a remarkable find.

In 1964, a rocket launched from the White Sands Range in New Mexico discovered a strong X-ray source in the constellation of Cygnus. Also in 1964, two sub-orbital rockets mapped out X-ray sources, pinning down the location of Cygnus X-1.

In 1971, observations by the Uhuru X-ray satellite telescope showed that the Cygnus X-1 source underwent rapid oscillations, suggesting it was a compact object that was smaller than the Sun. That same year, radio telescope observations linked the X-ray source to the star HDE226868. This blue supergiant would not itself produce X-ray emissions, implying that it had a companion. Also in 1971, astronomers at the Royal Greenwich Observatory and Toronto's David Dunlap Observatory made further observations of HDE226868. They confirmed that it was in a binary with a massive but compact object. And, in 1972, Charles Bolton at Toronto was the first to state definitively that this object was a black hole. This view was generally accepted by 1973.



Cygnus X-1 (location outlined in red). In this image, the blue supergiant companion star can be clearly seen to its right

would not escape from it. Such a 'dark star' would have to be immense. Even though the escape velocity from the surface of the Sun, for instance, is over 600km/s, it is still far lower than the speed of light.

Michell's theory was based on an incorrect assumption – that light was made up of normal particles that could be slowed down like any other projectile by the force of gravity. But the idea of these mysterious 'dark stars' faded into history.

Fast-forward to the 20th Century and Karl Schwarzschild revived the theories in the heat and horror of World War One. It was 1915 and the 41-year-old German physicist had volunteered to join up with the German army. Somehow, perhaps as a distraction from the devastation around him, he found time to think about Einstein's elegant equations and his brand-new theory of General Relativity. Einstein's equations are too complex to provide a universal solution, but Schwarzschild solved them for the special case of a spherical body that was not spinning.

It emerged from the mathematics that, if all the mass of that body was crammed into a sphere of a size now called the Schwarzschild radius, the distortion in space-time would be so great that light from the object would never escape. Anything closer than a sphere around the body of that radius would travel through a surface of no return – the black hole's event horizon.

DOWN THE HOLE

The most obvious source of such a body would be a collapsing star. In normal operation, a star's nuclear reactions fluff it up against the pull of gravity. But once those reactions start to fade, matter in the star can collapse. The expectation is that this collapse would be halted by a quantum effect called the Pauli exclusion principle, forming an intensely dense neutron star. If the star were massive enough, though, exceeding about three times the mass of the Sun, the exclusion principle should be overcome and the collapse would be unstoppable. In principle, the material in the black hole would continue to collapse all the way to a dimensionless point – a 'singularity' with infinite density and a force of gravity that headed off to infinity as it was approached. In reality, we don't know what would actually happen, because the singularity is an admission that our physics has broken down. For a good time after Schwarzschild, black holes were purely theoretical.

Or at least collapsed stars were, as they were yet to receive their more



CAST OF CHARACTERS

Five incredible physicists who have helped us with our understanding of black holes



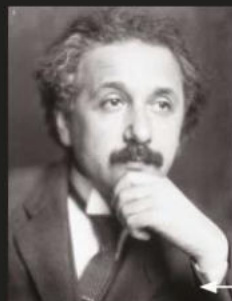
John Michell
(1724-1793)

Michell was born in Nottinghamshire and spent his academic life in Cambridge working on geology, gravity, magnetism and astronomy. After his marriage in 1764, he spent the rest of his life as a clergyman, most notably at Thornhill in Yorkshire. Here he continued with his scientific work from 1767 until his death in 1793.



Karl Schwarzschild
(1873-1916)

Schwarzschild was a German physicist and astronomer who was born in Frankfurt. He worked as a professor for several years in Göttingen, before moving on in 1909 to become director of the town's observatory before heading up the Potsdam Astrophysical Observatory. He volunteered for the German army in 1914 and died of a skin disease in 1916.



Albert Einstein
(1879-1955)

German-born Einstein is best known for his theories of Special Relativity and General Relativity, laying the foundations of quantum theory. Via Belgium and the UK, he moved to the USA in 1933 to escape Nazi Germany and took up a position at the Institute of Advanced Study in Princeton.



Kip Thorne
(1940-)

Thorne is an American astrophysicist whose studies of General Relativity have resulted in a wide range of predictions on black holes, wormholes and time travel. Thorne was consultant to the best cinematic representation of a black hole to date, the 2014 movie *Interstellar*.



Stephen Hawking
(1942-)

Cambridge-based Hawking is probably the most famous living physicist and has become iconic both for his bestselling book *A Brief History Of Time* and for defying the onset of motor neurone disease to continue working into his 70s. His work has largely involved the General Theory of Relativity and cosmology.

TIMELINE

Theories surrounding mysterious black holes have only been around since the 18th Century

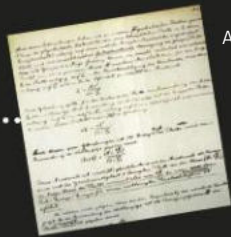
1915

John Michell's 'dark stars' paper is read at the Royal Society. He hoped to deduce the mass of stars from their effect on light, and thought a massive enough star would be able to stop light entirely.



1783

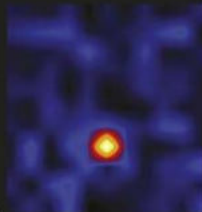
Albert Einstein publishes his field equations. This set of 10 equations at the heart of General Relativity describe gravity as a curvature of space and time.



1916

Soon after Einstein publishes the theory of General Relativity, Karl Schwarzschild publishes his paper with the first non-trivial solution. This is applied to a non-rotating sphere, derived the previous year.

1971



First candidate black hole is found. Cygnus X-1 is an X-ray source that was first detected in 1964 and is thought to be a binary star, where material from one star is accelerated into a black hole.

1995

Star S2 (Source 2) is observed by the Max Planck Institute and UCLA. It orbits an apparent supermassive black hole, Sagittarius A*, at the heart of our Milky Way.



2012

The best evidence to date of a star being ripped apart by a supermassive black hole is detected by the Pan-STARRS telescope on Hawaii and analysed by a Johns Hopkins University team.



➔ intriguing moniker. 'Black hole' is often ascribed to the American physicist John Wheeler, but its origins are shrouded in mystery. The term was first reported at an American Association for the Advancement of Science meeting in January 1964. It's not certain who used it, but Wheeler soon popularised it. It might seem that searching for black holes would be a waste of time. How do you see something that doesn't give off light? But, as the physics of black holes developed, scientists realised that indirect routes were available.

As astronomers can't see the hole itself, they need to look for its side effects. When matter is dragged into a spinning hole, and pretty well everything in the Universe does spin, it should produce an 'accretion disc', glowing brightly as a result of friction – and would also generate distinctive 'jets' from the poles. Then there are the gravitational effects. We might see nearby bodies influenced by the black hole. This is a venerable technique and was used in the past to infer the existence of Neptune. Astronomers studied the way the orbits of the other planets were influenced by Neptune's gravitational pull.

Finally, there is 'Hawking radiation'. Stephen Hawking surprised himself when in 1974 he realised that black holes couldn't truly be black. The idea came from his understanding of quantum physics – the science governing very small things – and in particular the 'uncertainty principle'. This said that localised energy can fluctuate significantly over small periods of time, allowing pairs of quantum particles to emerge and then disappear again before they are observed. If this happens near a black hole's event horizon, one of these 'virtual' particles could be pulled in while the other flies off. These stray particles make up Hawking radiation. This is unlikely to be detectable at any great distance.

After Schwarzschild's solution, black holes seemed the natural end for the right kind of stars with masses at least three times that of the Sun. But this particular scale is not a limitation of the black hole itself, merely the formation mechanism. In principle, black holes could exist on any scale from the microscopic all the way through to millions of times the mass of the Sun. There are broadly four categories, two of which have probably been detected.

At the tiny, totally hypothetical end of the scale are micro black holes and quantum black holes. A micro black hole would form, for instance, if the Earth collapsed, forming an event horizon about 9mm across, though thankfully there is

NEED TO KNOW

A handy list of the terminology connected to the study of black holes

1 ACCRETION DISC

Rotating matter is pulled into a disc shape by a star (part of the formation process of a solar system). In the case of black holes, nearby matter is accelerated intensely by gravity, giving off a bright glow.

2 JET

Streams of matter accelerated to nearly the speed of light are emitted at right angles to the accretion disc. The cause of these jets is uncertain, though they may be the result of a complex magnetic field.

3 PAULI EXCLUSION PRINCIPLE

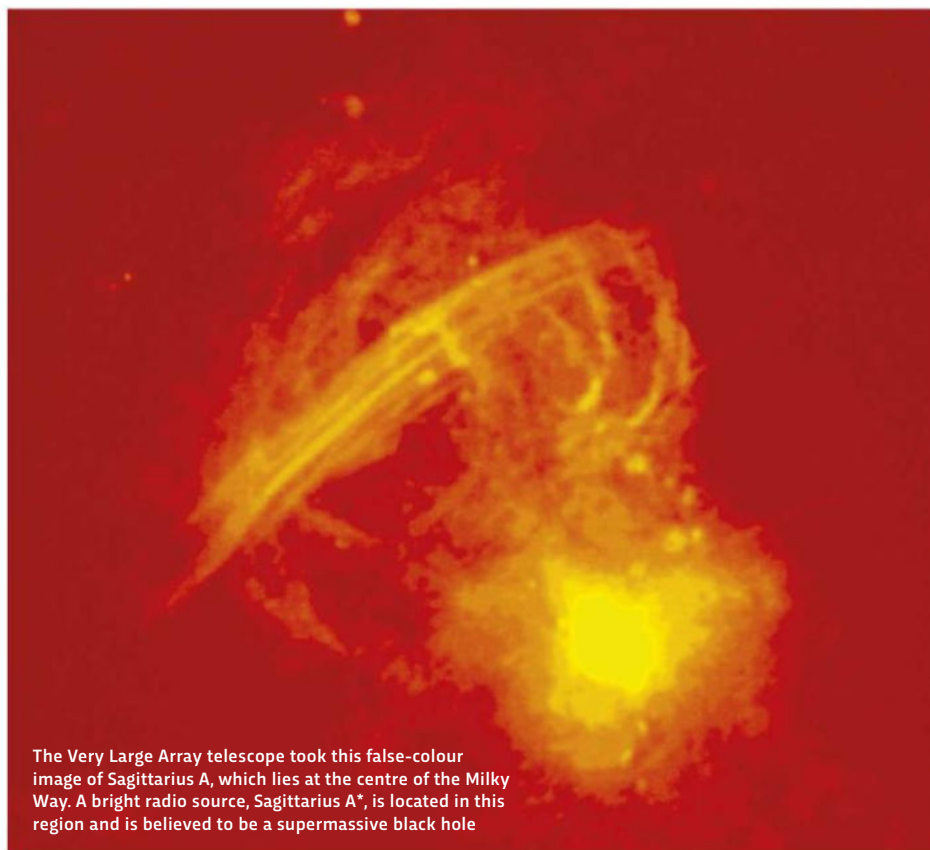
This principle of quantum mechanics establishes that two fermions (a type of subatomic particle) cannot be in an identical quantum state. This results in 'exchange interaction', which is like a short-range force keeping fermions apart – except in extreme conditions like black hole formation.

4 SINGULARITY

In the case of astrophysics, a singularity is a mathematically predicted condition where space-time becomes so locally distorted by gravitation that the force of gravity tends to infinity and current theories of physics break down.

no known mechanism for this to occur. Quantum black holes are even smaller, from a scale of around 5,000 protons up. In principle, they could be produced in a particle accelerator and would almost immediately decay. Current accelerators don't have the energy to produce one unaided, but if the Universe has extra dimensions, this could reduce the energy threshold to something accessible.

The best evidence we have for conventional black holes, formed from the collapse of a dying star, is X-ray binaries. In these objects, material is accelerated from one normal star into an invisible star, giving off X-rays. This can happen with a neutron star, but if the 'eating' star has more than about three times the mass of the Sun, it should in theory be a black hole.



The Very Large Array telescope took this false-colour image of Sagittarius A, which lies at the centre of the Milky Way. A bright radio source, Sagittarius A*, is located in this region and is believed to be a supermassive black hole

The first X-ray binary widely recognised as containing a black hole was Cygnus X-1. A powerful X-ray source was detected in 1964 and was identified as a black hole candidate in 1971. A blue supergiant star in the binary was being stripped of material by the X-ray source, which appeared to have a mass in the region of 9 to 15 times that of the Sun. In 1975, Kip Thorne and Stephen Hawking made a bet as to whether this was, indeed, a black hole. Hawking, on the 'no' side, paid up in 1990 when better observational data was obtained.

BACK TO BLACK

Since 1990, the identification of Cygnus X-1 has become less certain. This is because the companion star is very large, making it difficult to be sure of the mass of its 'compact object' companion. Many other candidates have been detected since, although evidence remains indirect and is based on theoretical assumptions about the maximum size of a neutron star that may not be borne out in practice.

Supermassive black holes are thought to exist at the heart of most galaxies, possibly forming from the collapse of a dense gas cloud in the galaxy's early life. Such black holes may play a significant

role in galaxy formation, giving the galaxy a hub to coalesce around. Candidates have been detected at many galactic centres, thanks to unusually high electromagnetic emissions from these regions, and the odd motion of nearby stars.

A star called S2 orbits the centre of the Milky Way at about four times the radius of the orbit of Neptune. From S2's path, it seems likely it's orbiting something with a mass of about 4.3 million times that of the Sun. The object matches the position of an intense radio source called Sagittarius A*, and there is currently no other explanation for this except a supermassive black hole. Elsewhere, stellar destruction gives a clue. Unusually bright light signatures in distant galaxies are thought to be stars being ripped apart by supermassive black holes.

All is not certain, though. A 2014 study suggested black holes won't form at all. The authors believed that as a star collapses, Hawking radiation would reduce the mass of the star sufficiently that the black hole never reaches completion. There would be an ultra-dense body acting like a black hole, but without the singularity or the event horizon. The paper isn't universally accepted, but illustrates how our understanding of black holes is primarily driven by theory. Whatever the reality, we can expect more surprises. ■

WHERE ARE ALL THE HABITABLE PLANETS?

*The number of known planets
is increasing all the time, but how
soon can we expect to find life?
STUART CLARK takes a closer look*

In March 2015, a team at the Niels Bohr Institute in Copenhagen used a 250-year-old equation called the Titius-Bode Law to predict the number of habitable planets. The researchers stated that billions of stars will have one to three planets in their 'Goldilocks Zone', also known as a habitable zone (see page 93). While the law gives a simple means of predicting the orbits of planets around a star, it isn't particularly accurate – even when applied to the Solar System.

Still, a lot of researchers believe that there are a significant number of Earth-like planets out there somewhere, many even within the Milky Way. Astronomers

call these Earth-like planets 'Earth analogues'. At the time of writing, there are 1,211 known planetary systems, with 482 of those sporting more than one planet. The current total of known planets sits at 1,918. These numbers increase all the time as new discoveries are made by various space programmes.

Some of the planets so far observed are Earth-sized, some are in similar orbits to Earth, and some are around Sun-like stars. But not a single one ticks all three of these criteria. Astonishingly, of these hundreds of planets, not one is Earth's twin. Does this mean that Earth analogues are rare? With several missions planned for the coming years by NASA and others, will we soon find our planet's sibling?

Prof Geoffrey Marcy, from the University of California at Berkeley, was one of the first people to find planets around other stars. Back in 1995, he began reporting a string of planetary discoveries that continues to this day. In 2013, he and two colleagues began to wonder how close the nearest Earth-twin might be.

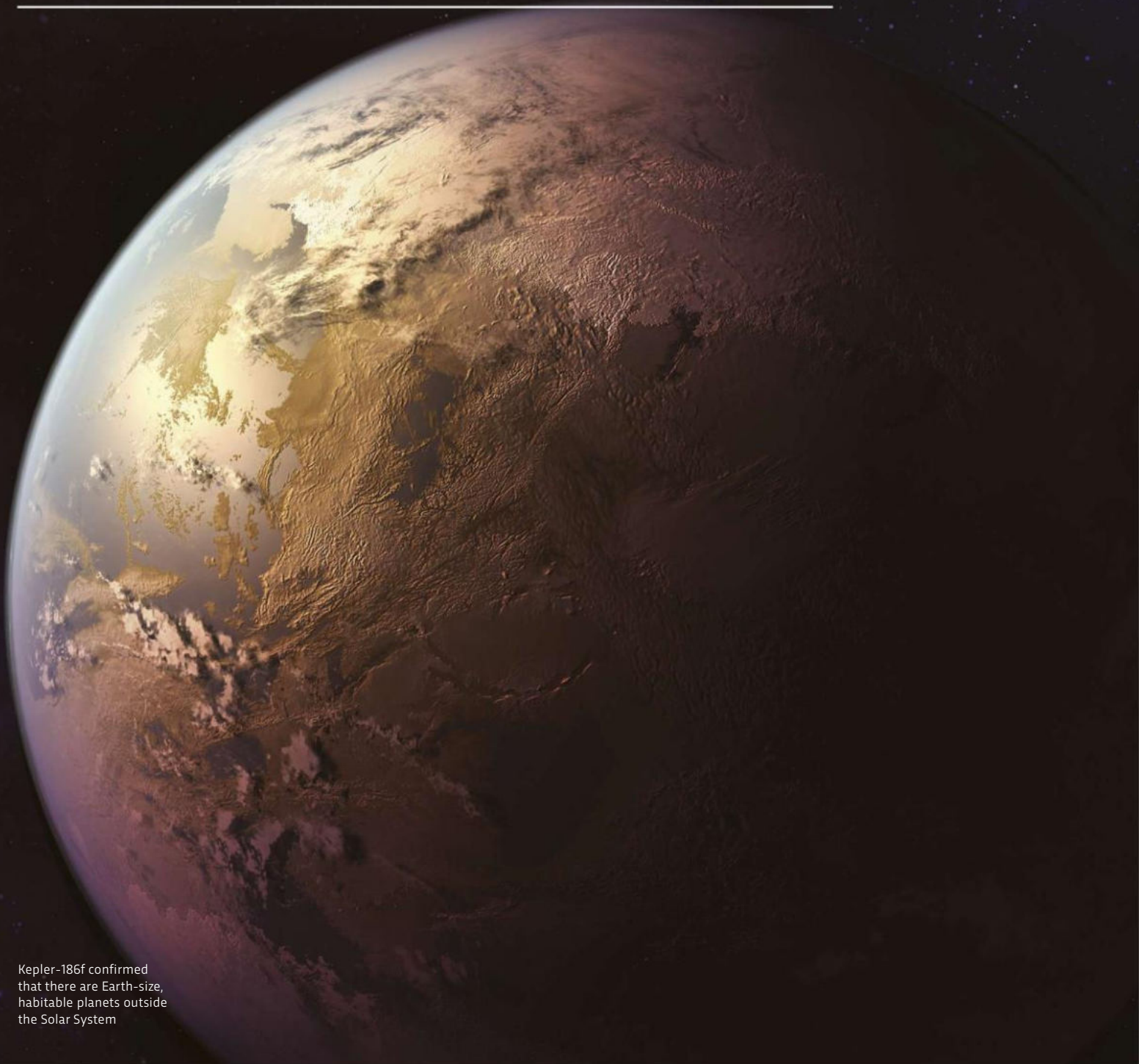
To find out, they trawled through data collected by the Kepler telescope. Launched in 2009, it continually monitored 145,000 stars until 2013, when a malfunction in its guidance system ended the mission. Marcy and colleagues analysed data from 42,000 stars in the survey. The signature they were looking for was a dimming in the star's light. When a planet passes in front of its



An artist's impression of an alien planetary system in the Andromeda galaxy

“The nearest Sun-like star with an Earth-size planet in its habitable zone is probably only 12 light-years away and can be seen with the naked eye”

Erik Petigura, University of California at Berkeley



Kepler-186f confirmed
that there are Earth-size,
habitable planets outside
the Solar System

parent star, its silhouette dims the star slightly and the telescope can measure this.

Using this technique, they discovered 603 planets. Ten were more or less Earth-sized and received something comparable to the light that Earth receives. None of the planets were Earth's twin, but in analysing the results statistically, they reached the conclusion that one in five Sun-like stars could harbour an Earth analogue.

"When you look up at the thousands of stars in the night sky, the nearest Sun-like star with an Earth-size planet in its habitable zone is probably only 12 light-years away and can be seen with the naked eye. That is amazing," said UC Berkeley graduate student Erik Petigura, who led the analysis of the Kepler data.

To help quantify the Earth-like properties of a planet, astronomers have concocted the Earth Similarity Index (ESI). It looks at a planet's radius, density, escape velocity and surface temperature and compares it to Earth. Planets are given a grade on a scale between 0 and 1, with a score of 1 indicating a planet exactly like Earth.

Using this scale, the planet most similar to Earth is KOI-1686.01. KOI stands for Kepler Object of Interest and is a temporary designation given to planet

candidates before they are confirmed. In this case, KOI-1686.01 is 1.33 times the radius of Earth. Although it orbits a dim red dwarf star, it is so close that it receives enough heat to allow surface water to be liquid. When everything was evaluated, its ESI came out to be 0.89. In our own Solar System, Mars has an ESI of just 0.69. Unfortunately, follow-up observations have failed to spot the planet for a second time.

WATER WORLD

To be counted as real, a planet must be seen first as a dimming of the star, before being confirmed using a ground-based telescope to look for the wobble on the star that the planet's gravity causes.

So, no second Earths yet. But that doesn't mean that some of the planets so far detected cannot be habitable. They'd just be more like Earth's cousins than Earth's twins. "For me, two planets stand out head and shoulders above all the others," says Marcy. "The first is Kepler-186f. This is almost exactly Earth-sized but only receives about one-third of the warmth from its star that Earth receives from the Sun. The second is Kepler-62f. This is 1.4 times bigger than Earth and receives around 40 per cent of Earth's energy."



Prof Sara Seager is confident that if there are Earth-like planets out there, her team will find them

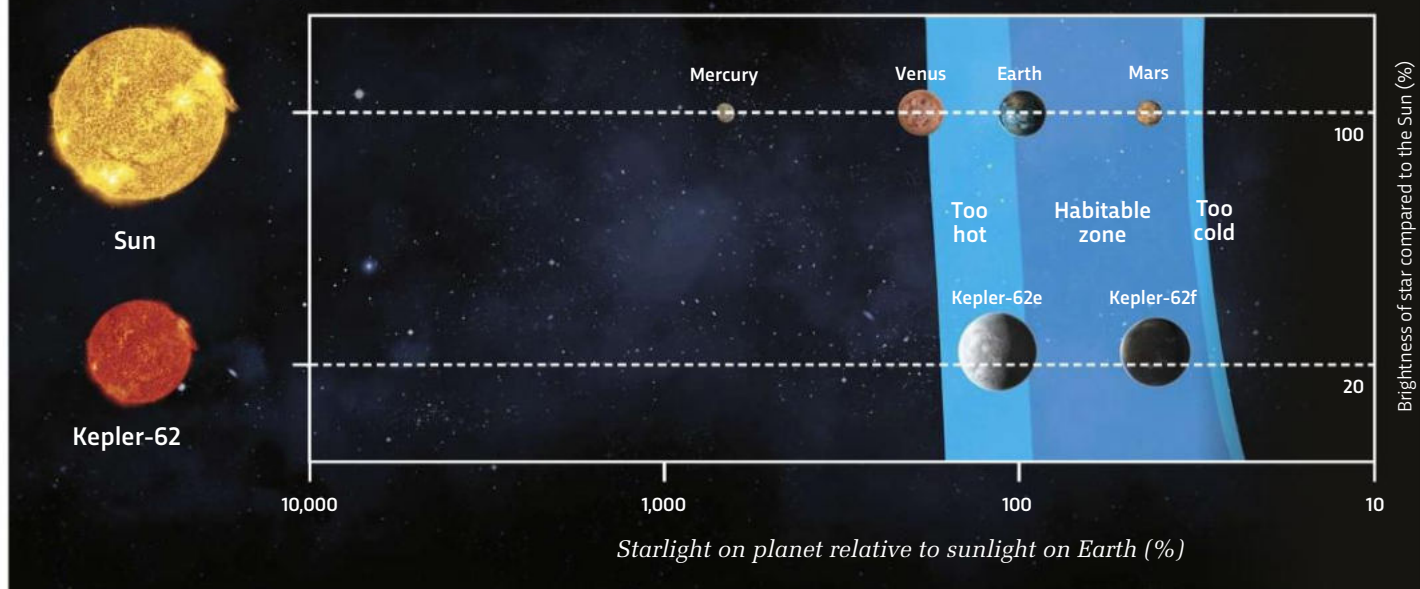
Habitability rests, first and foremost, on the planet being warm enough for liquid water to exist so that biochemical interactions can take place. A planet receiving much less energy than Earth receives from the Sun may seem as if it is too cold, but a planet's atmosphere can play a big role.

We hear a lot about the greenhouse effect, which is an



EXPLAINED: THE 'GOLDILOCKS ZONE'

This is the region around a star where the atmospheric conditions for orbiting planets are 'just right' to support liquid water. The exact location of the zone varies depending on how hot the star is...



Artists' impressions of some of the exciting exoplanets orbiting stars other than our own

EARTH 2.0?

Kepler was specifically designed to scan our region of the Milky Way for planets in the habitable zones of their central stars. Here are a few candidates that could support life...

KEPLER-438B

This planet was confirmed on 6 January 2015.

Kepler-438b is thought to be a rocky planet and is just 1.12 times the radius of Earth. It is situated 470 light-years away, where it orbits a red dwarf star once every 35.2 days. Even though its star is cooler than the Sun, its close proximity does mean that it receives 1.38 times the solar energy that Earth does.

KEPLER-442B

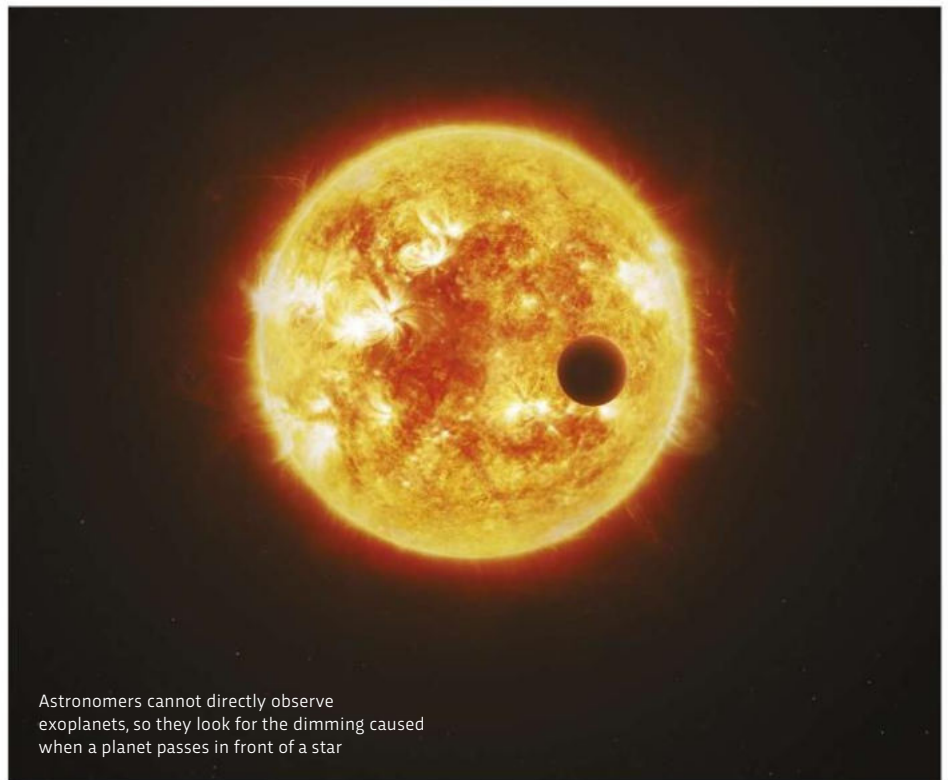
This planet is 1,120 light-years from Earth and 1.34 times our planet's radius. Although its parent star is a little cooler than the Sun, the planet's orbit means that it receives 0.66 of Earth's input energy. Kepler-442b orbits its parent star once every 112 days. Its discovery was announced at the same time as Kepler-438b.

→ atmosphere's ability to trap heat. Because of its association with industrial waste gases, we tend to think of it in a negative way, yet we rely on the greenhouse effect's warming action to keep the Earth habitable.

"Earth would be freezing without a greenhouse effect," confirms Marcy. So his two choices would have to rely on a greenhouse effect to compensate for the lack of energy they receive directly. In the case of Kepler-62f, its larger size will generate more gravity, thus ensuring a thicker atmosphere than Earth, which boosts its greenhouse effect.

A new generation of searches for habitable planets is on the horizon, with two new space missions that will follow on from the techniques of Kepler. They are being developed on either side of the Atlantic, and both rely on the transit method of detection. More sensitive telescope detectors will allow smaller planets to be seen.

The European Space Agency (ESA) is building CHEOPS (CHAracterising ExOPlanet Satellite) for launch in 2017. It will study nearby star systems that are



Astronomers cannot directly observe exoplanets, so they look for the dimming caused when a planet passes in front of a star



KEPLER-186F

Kepler-186f was announced in April 2014 and is perhaps the closest match to Earth so far. Although some began dubbing it Earth 2.0, it's not identical. While it is 1.1 times the radius of Earth, its star is dimmer than the Sun and Kepler 186f receives just a third of Earth's input energy.

It was the first Earth-size planet to be found orbiting in the habitable zone of a star.



KEPLER-62F

This is the outermost of a five-planet system orbiting the star Kepler-62. At 1.4 times the radius of our planet, it is termed a super-Earth. It receives just 0.41 times the amount of solar energy of the Earth, but its extra bulk will provide more gravity to attract a thicker atmosphere that could give rise to a lifesaving greenhouse effect.



KEPLER-62E

This planet is a sister world to Kepler-62f and is another super-Earth. It is located at the inner edge of the star's habitable zone, so it receives more energy than the Earth.

The discovery of the two potentially habitable worlds around Kepler-62 prompted a congressional hearing in the US dubbed 'Exoplanet Discoveries: Have We Found Other Earths?'

already known to have planets, with a goal of measuring those planets' radii and to look for other worlds that have so far escaped detection.

A CLOSER LOOK

Simultaneously, NASA is planning the Transiting Exoplanet Survey Satellite (TESS). This too will launch in 2017. It will use four onboard wide-angle telescopes to survey half a million stars across the sky. The mission team estimates that TESS could find between 1,000-10,000 planets.

The driving scientist behind TESS is Prof Sara Seager of the Massachusetts Institute of Technology. She is in no doubt about the goals and abilities that TESS will have. "If there is a rocky planet transiting a small star in the habitable zone of that star, we will find it," she says.

Seager hit the headlines in 2013 when she described an equation that could be used to estimate how many planets with detectable signs of life may be discovered over the coming years.



The TESS telescope will monitor half a million stars for planets in their habitable zones

The various terms in the expression included the number of stars to be observed, the fraction of those stars that we expect to have planets in their habitable zone, and the fraction that have sufficient life to produce an observable signature. Seager estimated that some terms, like the number of stars observed, can be assigned real values. But other terms, such as the fraction that have detectable life signs, remain speculative. As a result, Seager's

equation cannot give a definitive answer – however, she still believes that it was still a worthwhile exercise. "I wanted the world to know that we are doing the real search for alien life," she defends.

The first step towards that goal is finding as many habitable planets as possible. Astronomers already have some in the bag, but CHEOPS and TESS should advance the search significantly. E.T. – we're coming! ■

MYSTERY MESSAGES FROM SPACE

*Strange signals from outside our Galaxy have baffled scientists. But are they of alien origin?
HAZEL MUIR leads our investigation*



Scientists revisiting archived observations made by the Parkes Observatory in New South Wales in 2007 noticed something odd. They saw a brief, yet extremely bright burst of radio waves that lasted just five milliseconds. Nothing like it had ever been seen before. But in April this year, a similar signal was reported on the other side of the world at Puerto Rico's Arecibo radio telescope.

Researchers now think there's good evidence that these 'fast radio bursts' (FRBs) are not only real, but very common – and they come from vast distances far beyond our own Galaxy. Nobody knows what causes them, but could they possibly be evidence of intelligent aliens trying to get our attention?

The Parkes Observatory has a vast 64m-diameter radio dish, which is one of the world's oldest large movable dishes. It recorded an FRB in 2001, although it wasn't until several years later that astronomers noticed the strange signal. Since 2007, they have shown that the Parkes radio dish has spotted at least half a dozen FRBs, all of them lasting just a few

thousandths of a second. They have all come from different directions on the sky.

All the Parkes observations suggest that the FRBs come from sources that are very far away, according to Prof Benjamin Stappers from the University of Manchester, whose team has analysed the bursts. "Radio waves are dispersed by electrons in interstellar and intergalactic space, like light shining through a prism to give you the different colours," he says. "This causes low-frequency radio waves to arrive at the telescope later than high-frequency waves."

The amount of dispersion the team measured in the FRBs suggests that the radio bursts came from sources millions or even billions of light-years away. "They must be outside our Galaxy," says Stappers.

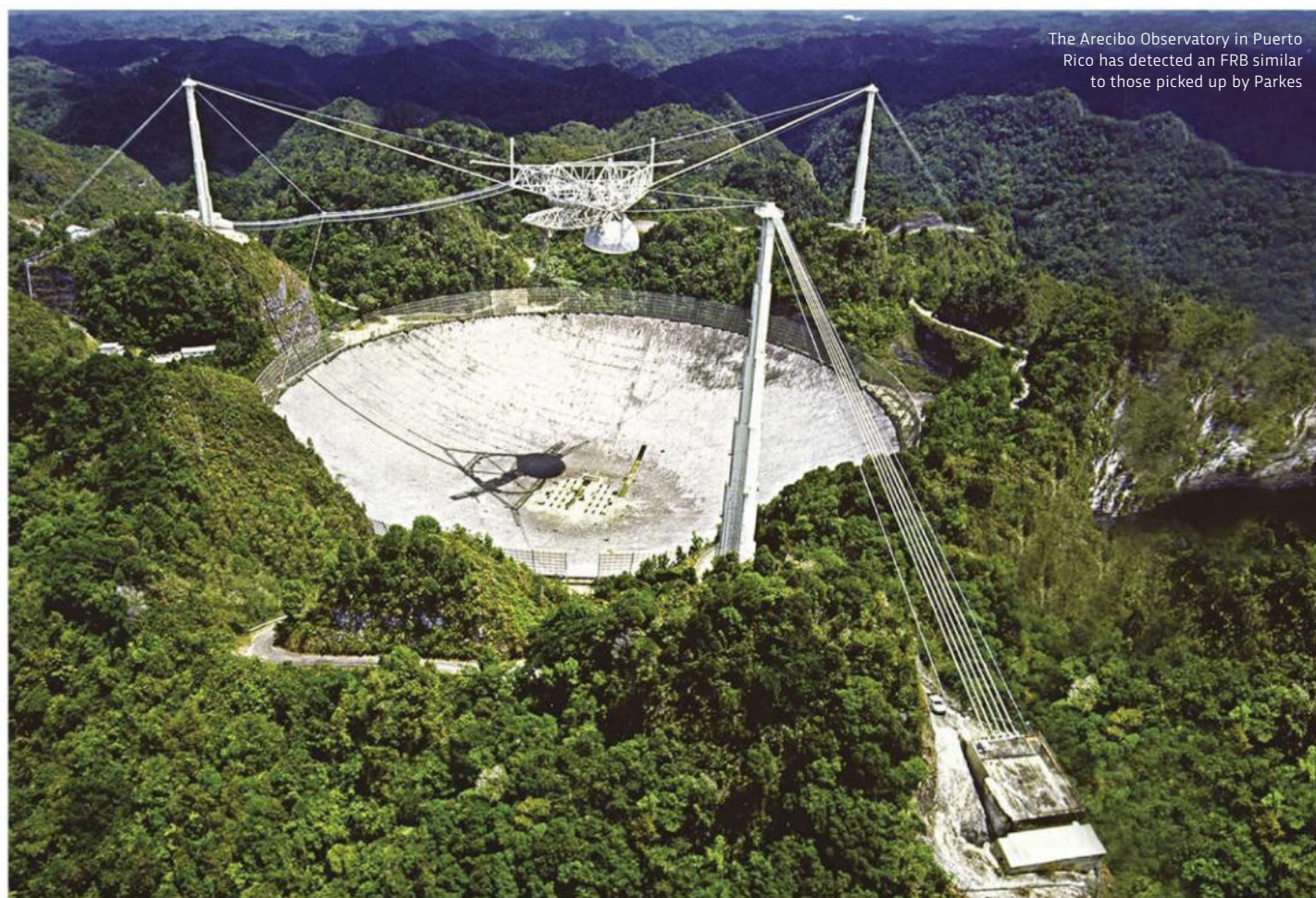
Until now, the findings have been controversial, because no other radio telescope had seen the peculiar short bursts. There was always the possibility that the Parkes dish had just picked up some local interference – maybe from a satellite or radar station – or that there was some kind of glitch with its electronics.

SIGNAL FROM ALIENS?

In 1967, a possible alien signal appeared in the constellation Vulpecula. Jocelyn Bell of Cambridge University (now Dame Jocelyn Bell Burnell) picked up regular radio 'beeps' that occurred every 1.3 seconds. They looked artificial, so her team named the source LGM-1 (for 'little green men'). However, LGM-1 turned out to be a rotating neutron star – the first one ever discovered.



Jocelyn Bell, discoverer of pulsars, in 1968



The Arecibo Observatory in Puerto Rico has detected an FRB similar to those picked up by Parkes

➔ Earlier this year, however, the plot thickened. Analysis of observations by the giant 305m-diameter Arecibo radio telescope in Puerto Rico have shown that it has also spotted a fast radio burst. It occurred on 2 November 2012 and had the same hallmarks as the Parkes FRBs, suggesting it came from far beyond the Milky Way.

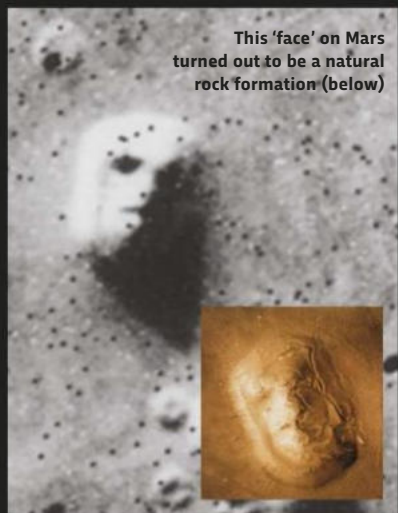
“Our result is important because it eliminates any doubt that these radio bursts are truly of cosmic origin,” explains Professor Victoria Kaspi from McGill University in Montreal, Canada, who headed the Arecibo survey that detected this FRB. “The radio waves show every sign of having come from far outside our Galaxy, which is a really exciting prospect.”

Dr Laura Spitler from the Max Planck Institute for Radio Astronomy in Bonn, Germany, who led the analysis of the Arecibo signal, adds that the observations now look extremely compelling. “The brightness and duration of this event, and the inferred rate at which these bursts occur, are all consistent with

FACE ON MARS

In 1976, NASA's Viking 1 spacecraft spotted a shadowy feature on Mars that looked uncannily like a human face. Many people jumped to the conclusion that it was an alien monument, possibly designed to send a message that a civilisation once existed on the planet.

But the excitement was brief. Later images showed it was simply a Martian mesa (a high plateau with steep sides) that was casting peculiar shadows, making it look like a human visage.



This 'face' on Mars turned out to be a natural rock formation (below)

THE ALIEN HUNTER

Douglas Vakoch is Director of Interstellar Message Composition at the SETI Institute in California



What would convince you that a signal was potentially alien?

We'd get excited if the signal looked different from anything that nature can make and if it came from a specific point in outer space, like a nearby star. Also, the signal would need to repeat.

How would you decode it?

First we'd look for patterns in the signal, like simple counting. And then we'd look for ways to connect those patterns to the real world. We can use counting, for example, to organise the chemical elements into the periodic table, and we'd hope scientists on other planets would recognise this pattern in nature, too.

What would the message say?

A message from extraterrestrials won't be in English or Chinese or Swahili. But if we get a message from aliens, we know they can build radio transmitters. They'd need

to know basic maths and science, like $1 + 2 = 3$, so that's how a message might start.

But if they only told us about things we already know, then what's the point? I hope they'd also tell us something about their culture, like their art or music.

What would convince you that you'd cracked an alien code?

I'd be convinced that we understood the message if it showed us something new – something we could later confirm with our own science. Then we'd know we weren't just projecting our own hopes and desires onto this alien message.

After decoding, what would you do about it and who would you tell?

Decoding a message could take decades. Long before then, we'd have told the whole world about it. But then we'd face the most critical questions: should we reply and, if we do, what should we say?

the properties of the bursts previously detected by the Parkes telescope in Australia,” she explains.

POSSIBLE CAUSES

So what causes these extremely bright radio bursts? So far they're a complete enigma, says Stappers. Possibilities include a range of exotic astrophysical objects, such as evaporating black holes or mergers between neutron stars. Neutron stars are the collapsed remains of the cores of massive stars that imploded during supernova explosions.

“Another possibility is that they are bursts much brighter than the giant pulses seen from some pulsars,” adds Professor James Cordes from Cornell University. Pulsars are rapidly spinning neutron stars that emit radio beams from their poles, and these can appear as radio pulses as they sweep across Earth like lighthouse beams.

But is there any chance that the fast radio bursts are messages from extraterrestrials trying to contact us? It seems unlikely. One reason is that the bursts are probably very common and

“The radio waves show every sign of having come from outside our Galaxy, which is a really exciting prospect”

seem to come from random directions on the sky. Scientists have only detected a handful of them so far, but they think that if huge radio telescopes were monitoring all of the sky all the time, they'd see roughly 10,000 of the bursts each day. It seems odd that aliens on thousands of planets in different parts of the cosmos would all contact us in the same manner.

The natural-looking patterns of the FRBs are further evidence that they are not of alien origin. Light emissions from

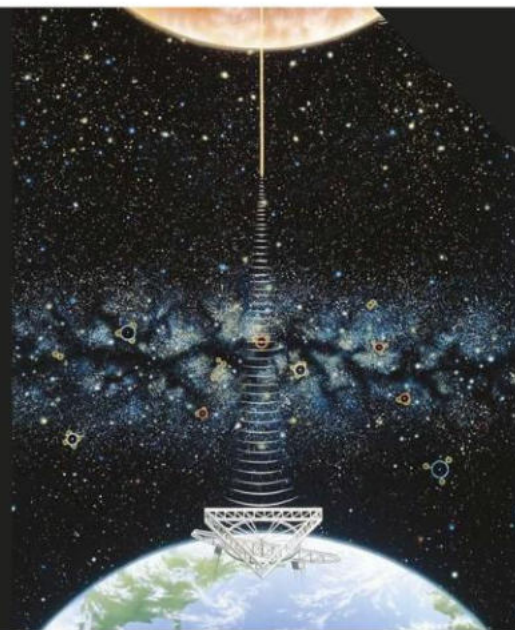
natural astronomical sources are usually broadband, and smeared out over a wide band of wavelengths. Narrowband signals with a waveband spanning only a few Hertz wide or less are typical from a purpose-built transmitter. And that doesn't fit with the FRBs, which have multiple wavelengths.

According to researchers involved in the search for extraterrestrial intelligence (SETI), another problem is repetition. No one has seen any FRBs repeat in the same patch of sky. However, it's impossible to rule out the idea that they never repeat. Maybe the repetition just takes a very long time, and repeats could be detected in future. For now, interpreting the bursts is just too difficult. Telescopes under construction in Australia and South Africa have the potential to detect more FRBs, and this could clarify the nature of these odd events.

FALSE ALARMS

At the Arecibo Observatory in Puerto Rico, false alarms of alien communications happen regularly. Often, the dish picks up a narrowband signal that doesn't look like anything natural.

But it usually takes only a matter of minutes to rule out alien communications because the signal persists even when the telescope monitors a different patch of sky. This suggests that the message is coming from a satellite or one of Puerto Rico's many radar and telecoms installations – a bugbear for SETI researchers.



Another observatory that should pick them up is CHIME (Canadian Hydrogen Intensity Mapping Experiment) in British Columbia, Canada. CHIME is an innovative new radio telescope that will have five cylindrical reflectors with the approximate dimensions of snowboarding half-pipes, with radio receivers along each one's focus. The reflectors won't actually move, but they'll detect radio signals from half the sky each day as the Earth rotates.

ONGOING MYSTERY

Stappers says he has no personal hunch about what the sources of FRBs are, but he hopes that detecting more will resolve the issue. "We are working very hard to find more of them, and also to pinpoint them in the sky more accurately to try and find their host location," he says. "Are they in galaxies? And if so, where in the galaxy – in the centre?"

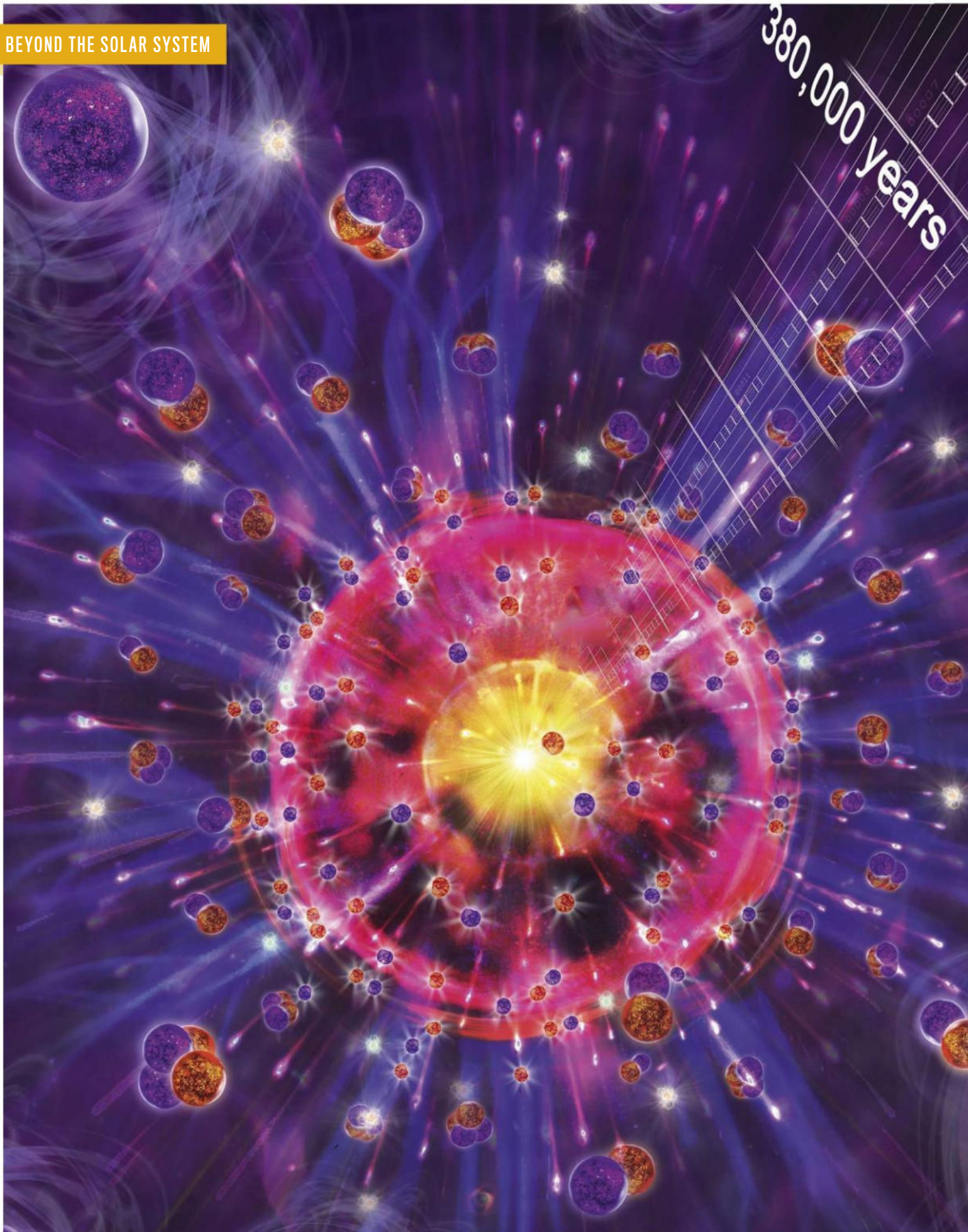
Until then, FRBs will have to be filed among unsolved mysteries, alongside the 'Wow! signal'. This strong, narrowband radio burst lasted more than a minute and was detected by Ohio's Big Ear radio telescope in 1977. Jerry Ehman, the astronomer who spotted it, wrote 'Wow!' on a printout of the signal. The Wow! name has stuck, but the signal has never been seen again.

The chances are that the fast radio bursts are something natural, rather than signals from little green men. But what causes them will no doubt baffle astronomers for some time. ■



Could FRBs come from a previously unknown type of pulsar? It's one of several possibilities

380,000 years



WELCOME TO THE MULTIVERSE

The recent detection of gravitational waves from the dawn of time has big implications. JOHN GRIBBIN reveals how it could confirm that our Universe is just one of many

There's really only one place to go if you want to watch the birth of the Universe: the South Pole. The temperature, which rarely climbs above -30°C , means that the air is always clear, which makes it an ideal spot to observe the infinitesimally minute traces of energy left over from our Universe's explosive birth. As a result, not one but three telescopes sit at the bottom of the Earth mapping out these tiny wavelengths of radiation scattered across space – what's known as the Cosmic Microwave Background (CMB). In 2014, it was one of these telescopes, the Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2), and its researchers that

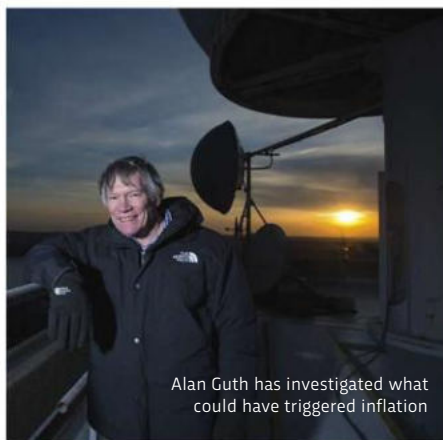
detected gravitational waves, confirming Einstein's theory of inflation.

Inflation explains how our Universe was kick-started, but it also says that other universes can be kick-started in the same way. So evidence for inflation is (at least circumstantial) evidence for the Multiverse. And evidence for inflation is what the BICEP2 scientists claim to have found.

SOMETHING FROM NOTHING

The Big Bang theory is one of the most well-established ideas in science. It explains how the Universe expanded from a hot, dense state (roughly the density of an atomic nucleus) into the pattern of stars and galaxies we see today. This hot, dense state was the Big Bang, and the idea was firmly established by the beginning of the 1980s. But how the Universe got into that hot, dense state remained a great mystery. What happened before the Big Bang?

It was the American cosmologist Alan Guth who realised that a process called symmetry breaking, akin to the way steam gives out latent heat when it condenses to form water, could have poured out energy in the first split-second of time. This could have pushed the Universe through a phase of rapid expansion called inflation and ended up with the Big Bang. (People often make the mistake of using the term Big Bang to include



Alan Guth has investigated what could have triggered inflation



WHICH TYPE IS RIGHT?

Cosmologists have defined four kinds of multiverse

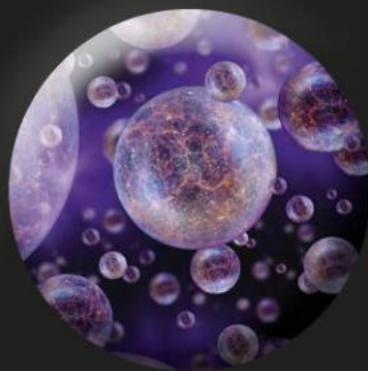
TYPE I

If the cosmos is infinite, there must be multiple copies of our Universe (defined as everything we can see out to the point where cosmological expansion is occurring at light speed) separated from us by vast distances. This is because there is only a finite number of ways to arrange all the particles in the Universe, just as there is only a finite number of ways to arrange the pieces on a chess board. Also, there must be multiple variations on the theme, with greater or lesser differences from our own Universe. *Red Dwarf* fans will be familiar with the possibilities.



TYPE II

The version that gains support from the BICEP2 results. Our Universe may be a bubble embedded in an expanding sea of space. There is no reason to think that it is the only bubble, so if this idea is correct there may be many other bubble Universes. But a single bubble in this Multiverse could itself be a Type I Multiverse.



TYPE III

The version familiar to anyone who has puzzled over the mystery of Schrödinger's cat. The puzzle of whether the 'cat in the box', threatened by a diabolical quantum device, is alive or dead can be resolved by saying that there are two Universes, one with a dead cat and one with a live cat. Apply the same reasoning to every possible outcome of every possible quantum event and you have the Type III Multiverse, also known as Many Worlds. Here, Universes are separated not by vast amounts of space, but are in some sense 'parallel' to one another in separate dimensions. This version has surfaced in *Doctor Who*.



TYPE IV

This type of Multiverse contains universes that are part of what is known as the 'cosmic landscape'. This is based on the idea that the laws of physics themselves may be different in different Universes. The 'landscape' is like a rolling plain, with different points on the plain representing different sets of laws, valleys being more stable configurations than hills. In our Universe, for example, there is one kind of electron, and three kinds of quark at the same particle level as the electron. In another Universe, there might be three kinds of electron and one kind of quark. Other possibilities are even more exotic. Mathematicians seem to love the idea, but most physicists fling up their hands in horror. Schrödinger's cat is simple by comparison.



BICEP2 at twilight in the clear air of Antarctica



→ inflation, but the crucial point is that inflation came before the Big Bang.) During inflation, the size of the Universe increases exponentially, doubling in size once every hundredth of a trillionth of a trillionth of a trillionth of a second. The idea was developed further by the Russian-born American Andrei Linde, and others, to explain how a Universe like ours can appear out of nothing at all.

It all depends on the idea of a quantum fluctuation, and the strange fact that the energy of a gravitational field is negative. Quantum theory says that particles can appear out of nothing at all, provided that they disappear again in a very short time. For example, an electron-positron pair might pop into existence, 'borrowing' energy from the vacuum, and promptly (within a tiny fraction of a second) disappear, giving the borrowed energy back. These are known as 'virtual' particles and, although you cannot see them directly, the influence of virtual particles can be discerned in the way 'real' particles interact with one another. Crucially, the more mass that is involved in such a fluctuation, the less time it can exist. So a proton-antiproton pair cannot exist for as long as an electron-positron pair, and so on.

NEGATIVE THOUGHTS

This is where the negativity of gravity comes in handy. If you imagine all the atoms that make up the Sun spread out to infinite distance, they would have zero gravitational energy, because the gravitational force between two particles is proportional to 1 divided by the square of the distance between them. But if the particles fell together to make a star, they would jostle one another and get hot as gravitational energy is



➔ released and converted into kinetic energy (something like this is indeed the way a star like the Sun forms). The gravitational field started out with zero energy, so now it has less than zero energy.

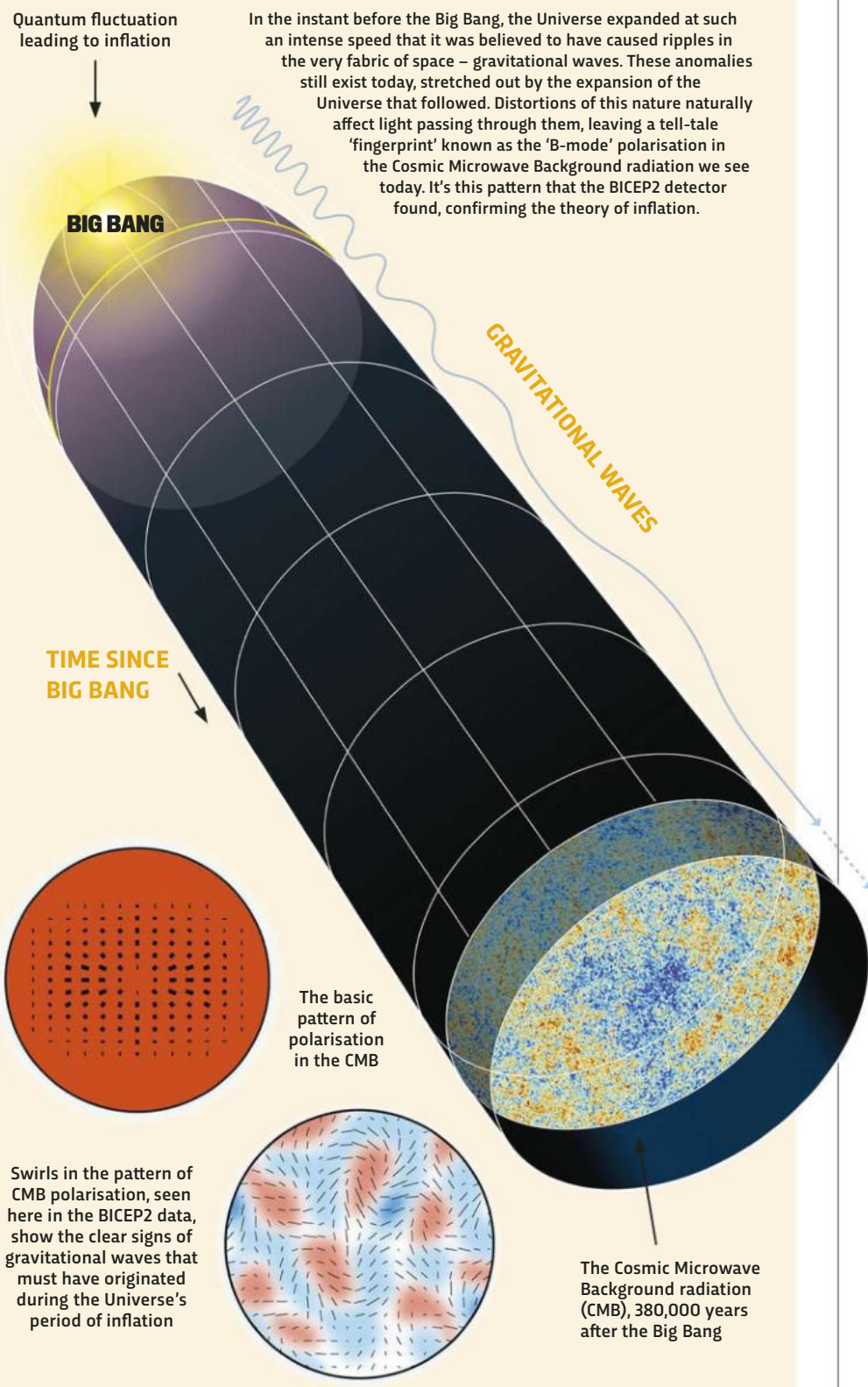
A simple calculation shows that if all the material collapsed to a point, the total amount of gravitational energy released would be exactly equal to the mass-energy of the star, given by Einstein's famous equation. This means that at that point, the mass-energy of the matter would be exactly cancelled out by the negative gravitational energy of the matter. You would have a blob of stuff with the mass of a star, but zero energy overall. It means that in a sense you could make a star out of nothing at all, as a concentration of matter that expanded away from a point.

If this seems mind-boggling, you're in good company. When the physicist George Gamow mentioned the idea to Albert Einstein one day, "Einstein stopped abruptly in his tracks, and, since we were crossing a street, several cars had to stop to avoid running us down".

What applies to a star also applies to a Universe. Quantum physics says that a fluctuation containing all the mass-energy of the Universe could arise from nothing at all, as a tiny, superdense seed. If this meant 'making' energy, as with an electron-positron pair, the quantum fluctuation would have to disappear quickly, giving the 'borrowed' energy back to the vacuum. But because the mass-energy would be exactly balanced by the negative gravitational energy, there is no quantum limit on the lifetime of such a fluctuation. You might think that the powerful gravity field would itself crush such an embryonic Universe out of existence. But that is where inflation comes in. The symmetry ➔

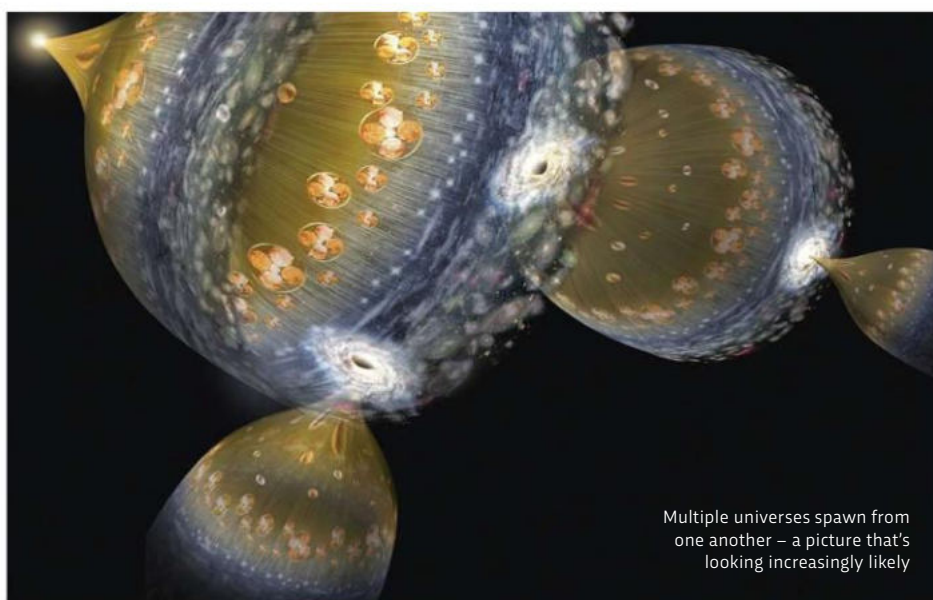
HOW BICEP2 CONFIRMED THE THEORY OF INFLATION

How BICEP2 confirmed the theory of inflation





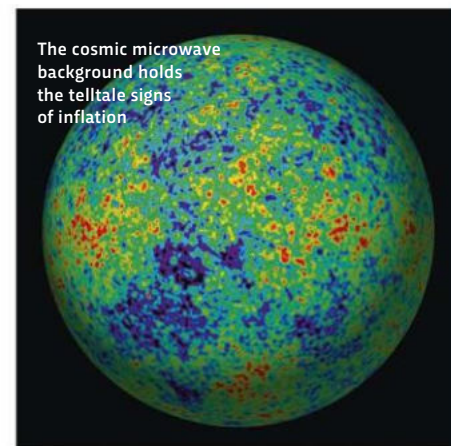
The Dark Sector Lab, about 1km from the South Pole, houses the Universe-probing BICEP2



Multiple universes spawn from one another – a picture that's looking increasingly likely

by Lee Smolin, who works at the Perimeter Institute in Canada. But don't worry. Such a new universe would not explode out into our Universe, destroying everything in its path. It would expand into its own set of dimensions, connected to us by a tiny wormhole. If this idea is correct, it might even be possible to make such a baby universe by making a tiny black hole in particle collisions using accelerators not much more powerful than the Large Hadron Collider.

These ideas are admittedly speculative. But there is a much less speculative, and simpler, version of inflation developed by Linde. A small tweak to the equations of the General Theory of



The cosmic microwave background holds the telltale signs of inflation

➔ breaking that Guth proposed can take this universal seed and whoosh it up into the hot Big Bang state, leaving a more leisurely expansion that can continue for billions of years as the Universe cools and forms stars and galaxies. Roughly speaking, everything in the observable Universe today was inflated from a region much smaller than a proton (actually less than a billionth the size of a proton) to about the size of a basketball within about

10^{-30} seconds. Only then did the Big Bang take over. "The Universe," says Guth, "is the ultimate free lunch."

BUBBLE UNIVERSES

But why stop at one Universe? If a quantum fluctuation can lead to the birth of our Universe, then quantum fluctuations within our Universe could lead to the birth of other baby universes – an idea explored

➔ Relativity produces a mathematical description of space that is always expanding exponentially fast – what Linde calls ‘eternal inflation’. This would be the background cosmos, everything there is. Within this inflating meta-world, there are occasionally places where inflation stops and these regions form bubbles within the inflating sea. Our Universe is such a bubble, and the implication is that there are other universes, other bubbles far away across the inflating sea, like the bubbles that form in the liquid when a fizzy drink is opened.

Like all good scientific ideas, this leads to a prediction. Since 1980, theorists

have come up with several more or less exotic variations on the inflation idea. But the simplest version makes a clear prediction. The repeated doubling in size of the Universe during the split-second that inflation lasted was violent enough to cause ripples in the structure of space; these ripples, known as gravitational waves, would have been stretched by the subsequent expansion of the Universe until they became almost a billion light-years long. Such huge structures in the Universe could not have been made in any other way. Distortions in space naturally affect light passing through them, and the primordial light passing through these

gravitational ripples is seen today in the form of the cosmic microwave background radiation. Inflation theory says that the distortions produced by the expanded gravitational waves should show up in the way that the background radiation is polarised. In particular, it should affect the so-called ‘B-mode’ polarisation, which is a measure of circular polarisation. The effect is to produce a swirly pattern when the polarisation is plotted on a map of the sky. This is exactly what the BICEP2 experiment has revealed. And the pattern is simple.

JUST RIGHT FOR LIFE

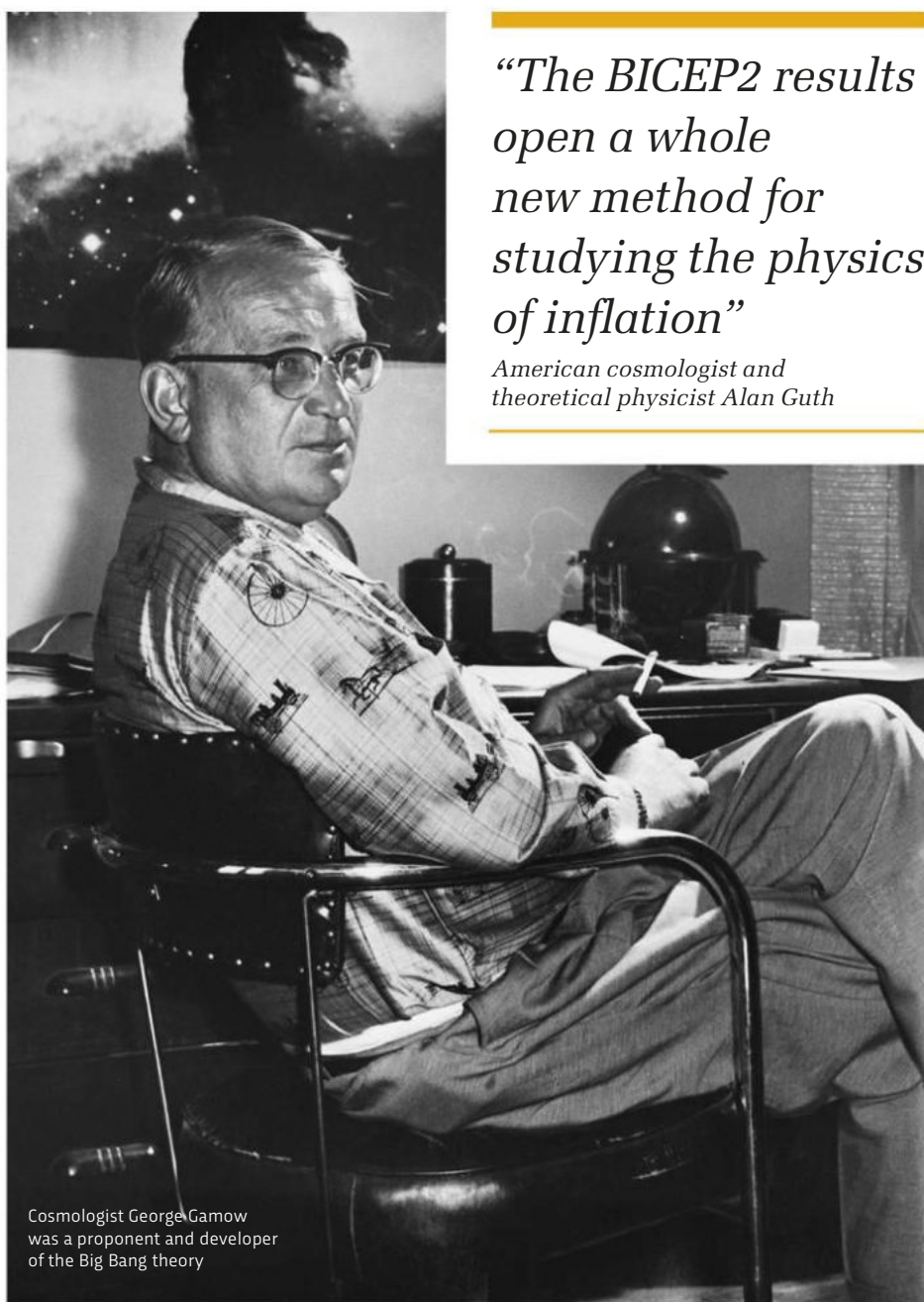
The experimental results match the predictions of the basic version of inflation – which, happily for the cosmologists, is the simplest version to work with. They also rule out models of the very early Universe which do not include inflation. Alan Guth is delighted by the news. “The results from BICEP2 are stunning. They found a gravitational wave signal that is stronger than we expected. Assuming that the result can be confirmed – and it most likely will – it opens a whole new method for studying the physics of inflation,” he says.

If other ‘bubble universes’ exist in the Multiverse, it’s possible that long ago one or more of them may have collided with our Universe, like two soap bubbles touching and moving apart. One effect of such a collision would be to leave a distinctive, but faint, disc-shaped pattern in the polarisation of the background radiation. Such rings would be too big to be seen by BICEP2, but cosmologists have worked out what kind of patterns should be seen as a result of collisions. Daniel Mortlock, of Imperial College London, says that the team “took great care to assess how likely it was that the possible bubble collision signatures could have arisen by chance.”

Perhaps the greatest significance of the new discovery, though, is the implication that our Universe is not unique. If eternal inflation is correct, and all the evidence says that it is, then our Universe is just one among many. Among other things, this explains why it seems so conveniently set up for the existence of life forms like us. If our Universe is unique this is a puzzle; if there are infinitely many universes, some suitable for life and some not, there will be nobody in ‘sterile’ universes to notice their existence. There will only be observers in ‘fertile’ universes. The fact that we are here to notice the Universe means that we live in a Universe suitable for life. ■

“The BICEP2 results open a whole new method for studying the physics of inflation”

American cosmologist and theoretical physicist Alan Guth



Cosmologist George Gamow was a proponent and developer of the Big Bang theory

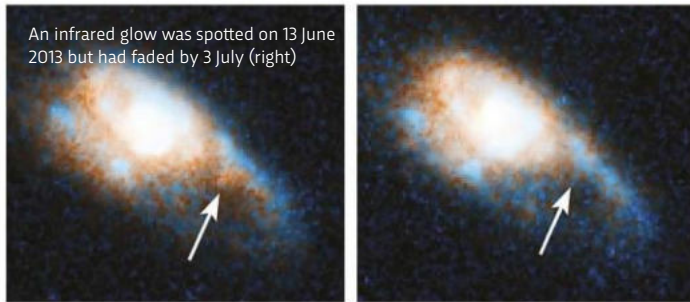


HUBBLE'S TOP 10 DISCOVERIES

The Hubble Space Telescope has been observing the Universe for a quarter of a century. AMY TYNDALL takes a look at some of its most incredible discoveries

Twenty-five years ago, one of the most famous and awe-inspiring pieces of technology – the Hubble Space Telescope – was launched. Hitching a ride with the Space Shuttle Discovery in 1990, Hubble was placed in low-Earth orbit, where it has been continuously observing the night sky ever since. Observations have been carried out across all wavelengths of light, from ultraviolet to infrared, which have given astronomers an unprecedented window on the Universe.

But what have they learned from its breathtaking pictures? To find out, we polled 100 professional astronomers around the world and the results are in...



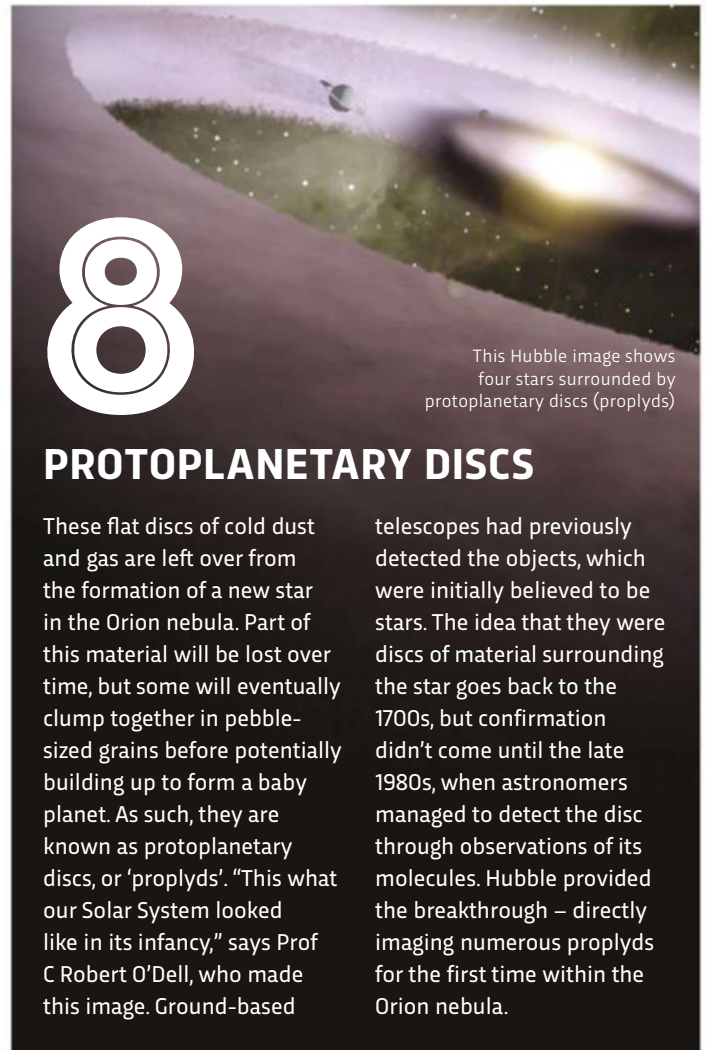
An infrared glow was spotted on 13 June 2013 but had faded by 3 July (right)

CAUSE OF GAMMA-RAY BURSTS

10

The fuzzy-looking galaxy above was home to one of the most energetic events in the Universe: a gamma-ray burst (GRB). These flashes of gamma-ray radiation are an enigma because they're so rare – a typical galaxy

produces only a few every million years. Yet they release as much energy in a few seconds as our Sun does in 10 billion years. On 3 June 2013, a GRB lasting one-tenth of a second occurred and was spotted by NASA's Swift satellite. When Hubble looked 10 days later, it found an infrared glow where the burst had been. But, by 3 July, it had faded. This disappearing glow was the dying embers of another kind of cosmic explosion – a kilonova – believed to be the result of extremely dense stars called 'neutron stars' merging. Since the kilonova was found in the same location as the GRB, it was the 'smoking gun' revealing that short GRBs could well be caused in the same way. The kilonova was investigated by Prof Nial Tanvir of Leicester University, who says Hubble played a vital role. "Although Swift discovered this particular short gamma-ray burst, and observations from ground-based telescopes gave us its precise position and distance, Hubble was the only option for seeing the faint kilonova emission."

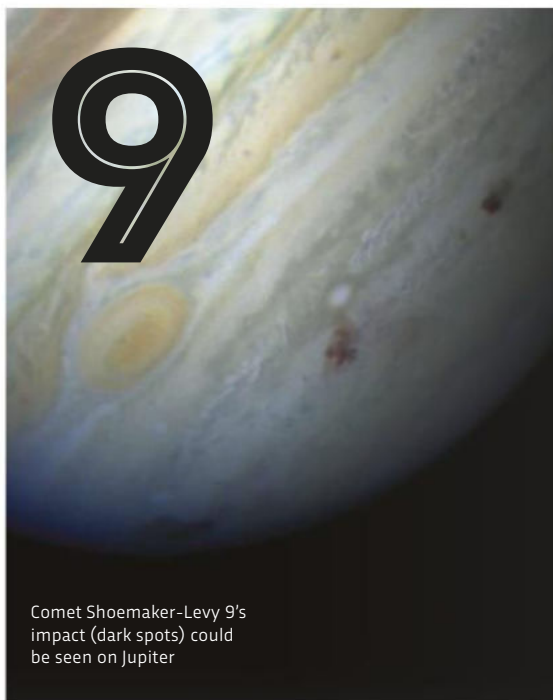


This Hubble image shows four stars surrounded by protoplanetary discs (proplyds)

PROTOPLANETARY DISCS

These flat discs of cold dust and gas are left over from the formation of a new star in the Orion nebula. Part of this material will be lost over time, but some will eventually clump together in pebble-sized grains before potentially building up to form a baby planet. As such, they are known as protoplanetary discs, or 'proplyds'. "This what our Solar System looked like in its infancy," says Prof C Robert O'Dell, who made this image. Ground-based

telescopes had previously detected the objects, which were initially believed to be stars. The idea that they were discs of material surrounding the star goes back to the 1700s, but confirmation didn't come until the late 1980s, when astronomers managed to detect the disc through observations of its molecules. Hubble provided the breakthrough – directly imaging numerous proplyds for the first time within the Orion nebula.



Comet Shoemaker-Levy 9's impact (dark spots) could be seen on Jupiter

HOW PLANETARY COLLISIONS WORK

On 16 July 1994, telescopic eyes were turned on Jupiter as the first of 21 fragments of the broken-up comet, Shoemaker-Levy 9, crashed into the planet. Blotches scarred the atmosphere for a month before fading away.

Hubble's observations provided a wealth of information about Jupiter's atmosphere. "Obvious waves emanated from the largest impacts, like ripples in a pond. From this, we could make deductions about the deep atmosphere and water below the clouds," explains

Dr Amy Simon, senior scientist for planetary atmospheres research at NASA Goddard in Maryland.

While ground-based observatories were also involved, Hubble was the only one that could look across an entire range of wavelengths, irrespective of the time of day or weather conditions. Ultraviolet was particularly important for imaging dust and aerosols whipped up by the impacts. "Hubble observed leftover debris and molecules high in the atmosphere for months, and even years, afterwards," says Dr Simon.

Hubble reveals individual stars in the galaxy M81, including Cepheid variables that were used to determine that the Universe is 13.8 billion years old

7

THE AGE OF THE UNIVERSE

This spiral galaxy, M81, was the first of many galaxies observed by Hubble to find the expansion rate, and therefore the age, of the Universe. "Before the launch of Hubble, there was a heated debate over whether the Universe was 10 or 20 billion years old," says Prof Wendy Freedman, an astronomer at the University of Chicago. Freedman set out to measure Cepheid variable stars – pulsating stars whose brightness increases and decreases over a timescale of days to months. By determining

the relationship between a Cepheid's brightness and its pulsation rate, it is possible to estimate its distance. Cepheids are the most accurate way of measuring the distances to galaxies, and for setting the expansion rate of the Universe.

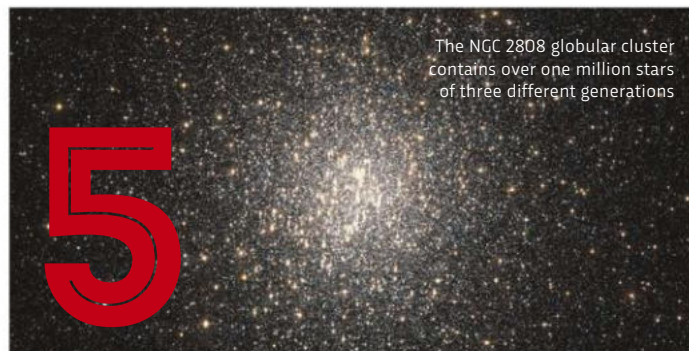
The high resolution of Hubble's instruments meant that the team was able to discover over 800 Cepheids in 24 nearby galaxies. The Hubble measurements helped to determine that the age of the Universe is 13.8 billion years.

SUPERMASSIVE BLACK HOLES

6

Black holes are difficult to find. Their intense gravitational force is so strong that not even light can escape their

pull, making them 'invisible'. But by measuring the speed of material that surrounds a black hole, it's possible to calculate its mass using the laws of gravity. If there is more mass than is accounted for by the stars we see, the rest could be due to a black hole. By the early 1990s, it was suspected that a supermassive black hole (SMBH) was at the centre of a handful of galaxies. "Soon after its launch, Hubble confirmed earlier SMBH detections by taking images five times sharper than those obtained from the ground," explains Dr Marc Sarzi from the University of Hertfordshire. Hubble became known as a 'black hole hunter', due to its ability to measure the speed of surrounding gas and stars. The results from its observations suggest they evolved together, as Dr Sarzi explains. "It has turned SMBHs from being exotic curiosities to an integral part of our understanding of galaxy formation."

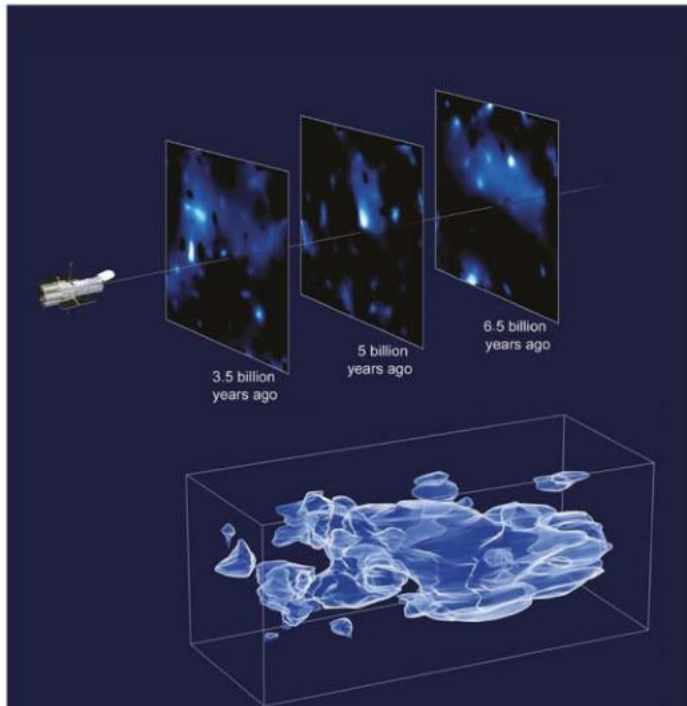


The NGC 2808 globular cluster contains over one million stars of three different generations

GENERATIONS OF STARS

Globular clusters are compact crowds of hundreds of thousands of stars bound together by gravity. For many years, the common consensus was that all the stars within must be very similar, having formed close together from the same dusty cloud. But, in 2005, Hubble measured the brightness and colours of stars inside the

NGC 2808 globular cluster. While only a single generation of stars was expected, three generations were actually found. Hubble's power to observe in both visible and ultraviolet light also made it easier to spot multiple populations of stars and track their evolutionary paths. It has now observed more than 60 globular clusters.



Hubble allowed scientists to create this 3D map of dark matter – the distance from Earth increases from left to right

4

DARK MATTER

This picture reveals the presence of something we can't see: 'dark matter'. The galaxies, stars and planets that we can see make up just 15 per cent of the Universe's matter. The remaining 85 per cent – is dark matter and it neither emits nor absorbs any known wavelength of light. "With this map, we saw for the first time where dark matter is," says Durham University physicist Dr Richard Massey. To construct it, half a million galaxies were observed by Hubble and ground-based telescopes. "When light travels across the Universe, it passes through all the intervening dark matter on its way to

us, leaving a telltale imprint of its journey. You can't see such faraway, faint galaxies from Earth because the atmosphere blurs the detail. This is why we needed Hubble," explains Massey. The dark matter bends the light in a 'gravitational lensing' effect, making the galaxies appear distorted. By observing this, it's possible to deduce where dark matter lies. It acts as 'scaffolding', along which galaxies are assembled. "When the first explorers reached the American West, they sat on a ridge and tried to understand the lie of the land. We were doing the same thing on a new frontier."

EXOPLANET ATMOSPHERES

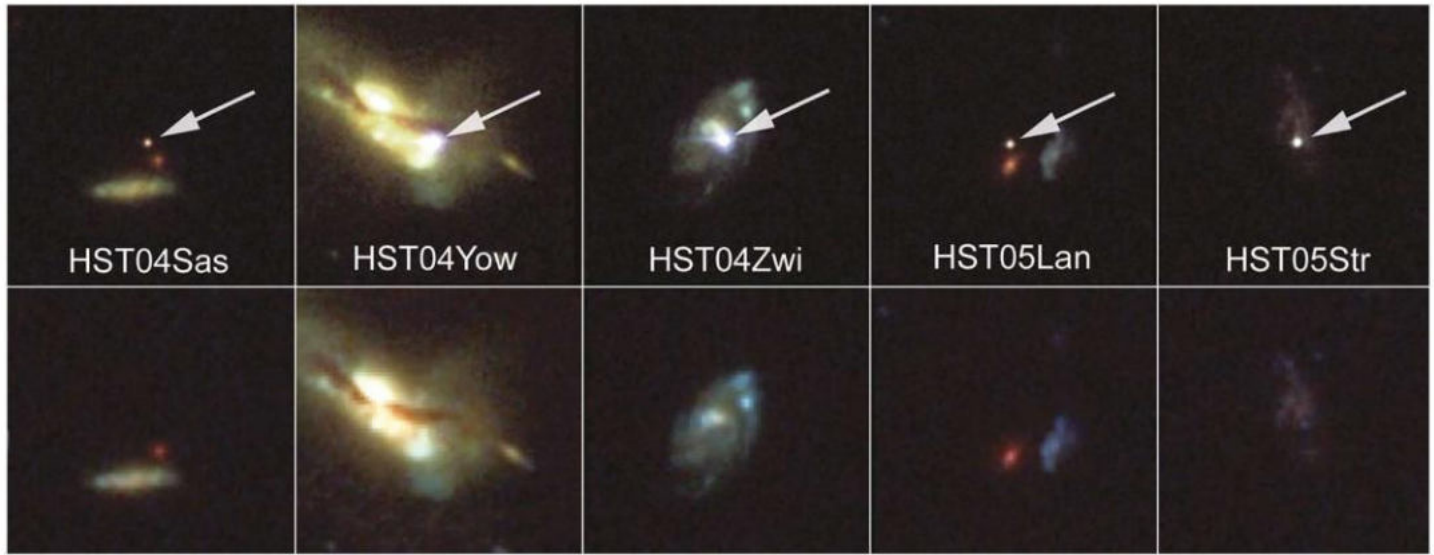
As of February 2015, 1,890 planets had been detected orbiting stars other than our Sun. An impressive photo of one of these 'exoplanets' has yet to be taken, but Hubble was first to detect the atmosphere of one of these alien worlds.

HD 209458-b, also known as Osiris, is a planet 150 light-years from Earth. Temperatures reach a scorching 1,100°C as it orbits just 6.4 million kilometres from its parent star. As the orbiting planet moves in front of the star, some of the light passes through the planet's atmosphere. This

is analysed by a spectrograph, which is an instrument that splits the light into constituent wavelengths, explains Prof David Charbonneau, leader of the team behind the discovery. "The idea was to gather spectra when the planet was in front of the star and when it moved away. By comparing them, we would search for the appearance of new features when the planet was in transit. This required an extremely stable platform that was free from the absorption effects of our atmosphere. Only Hubble could do it!"

Artist's impression of the planet Osiris, which lies 150 light-years from Earth





ACCELERATING THE EXPANSION OF THE UNIVERSE

These galaxies, hosting energetic supernovae (exploding stars), contributed to one of the most talked-about discoveries in recent

2

years. Not only is the expansion of the Universe accelerating, it is being fuelled by a phenomenon dubbed 'dark energy'.

In 1998, astronomers released new data on

how the brightness of supernovae changed over time. It showed light coming from the most distant exploding stars was fainter and more stretched (red-shifted) than predicted. It meant they were further away than astronomers calculated – a result that didn't fit with the existing idea that the tug of gravity was causing the expansion of the Universe to slow down. The expansion rate is not slowing at all. It's speeding up.

Hubble played a supporting role in this initial discovery by providing data for three of the supernovae the research team wanted to observe. Also, by finding and precisely measuring another 16 supernovae at distances up to 10 billion light-years away, Hubble was able to confirm not just the acceleration, but that the Universe had indeed been decelerating in earlier times, just as predicted.

HOW GALAXIES EVOLVE

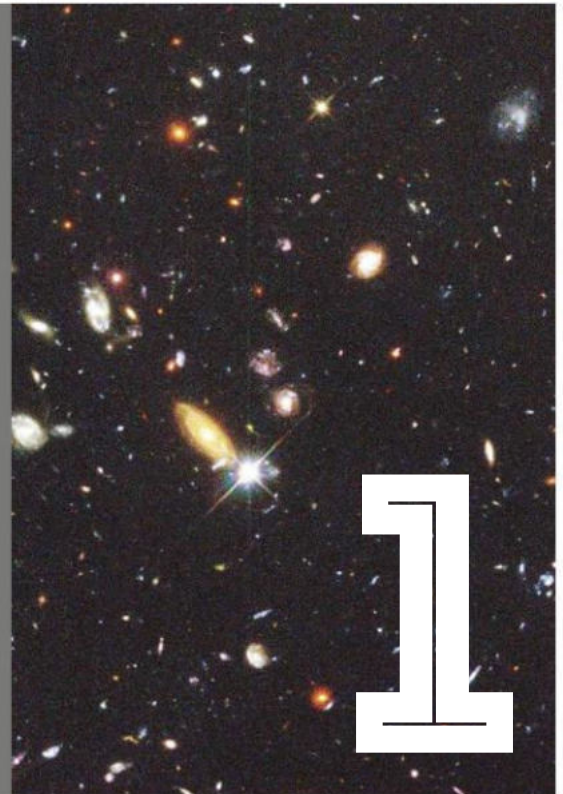
This image, dappled with beautiful shapes and a whole array of colours, changed the way we think about the distant Universe forever. One of Hubble's most famous images, the Hubble Deep Field (HDF) is a snapshot of a tiny patch of sky in the constellation Ursa Major. It covers an area of just one 24-millionth of the whole sky. And yet this minute window reveals around 3,000 galaxies crowded together, giving astronomers a vital window into the past.

There had been predictions that the light emitted from such distant objects would be stretched out so much that they would appear as nothing more than faint smudges against the blackness. They could not have been more wrong. This image, made up of 342 separate exposures taken over

more than 100 hours, showcased the power of Hubble. It revealed an incredible amount of detail and structure to galaxies that had never been seen before.

"A lot of astronomers were sceptical that we would learn a lot from simply pointing the telescope at a fairly arbitrary spot in the sky and taking long exposures," says Dr Henry Ferguson, a member of the original HDF team. However, the plethora of information that appeared convinced most that this was a good technique.

Today, astronomers are finding galaxies from a time when the Universe was only 500 million years old. As Dr Ferguson rightly – and excitedly – exclaims, "it is one of the most important observations ever made with any telescope!"



BEYOND HUBBLE

Ten other space telescopes with the unknown in their sights

CHANDRA X-RAY OBSERVATORY

Operated by: NASA

In service: 1999-

Originally scheduled to serve a five-year mission, Chandra was launched aboard Space Shuttle Columbia in July 1999. But it continues to orbit Earth today – at an altitude of 139,000km – detecting X-ray emission from particular regions of the Universe, such as exploded stars.



HERSCHEL SPACE OBSERVATORY

Operated by: European Space Agency

In service: 2009-2013

Named after William Herschel (the astronomer who discovered Uranus) and his collaborator/sister Caroline, Herschel was the largest infrared telescope ever launched. It collected a substantial amount of data during its lifespan, which ended when, as expected, its coolant supplies ran dry.



KEPLER

Operated by: NASA

In service: 2009-

Kepler was constructed to discover extrasolar planets orbiting their own stars. In the years since its launch, this planet-hunter has found in excess of 500 possible new planets, including Kepler-452b, thought to share more characteristics with Earth than any other planet yet discovered.



SPITZER SPACE TELESCOPE

Operated by: NASA

In service: 2003-

Spitzer is the fourth and final part of NASA's Great Observatories programme, along with the Hubble, Compton Gamma Ray Observatory and Chandra missions. Its infrared instruments allow it to observe what's otherwise invisible in our universe, relaying images of stars previously obscured by cosmic dust.



PLANCK OBSERVATORY

Operated by: European Space Agency

In service: 2009-2013

During its lifespan, Planck was described by the ESA as a cosmic time machine due to its success in enlightening us about the history of the Universe. It scanned deep space for cosmic radiation background, the oldest light in the Universe that was created just 380,000 years after the Big Bang.



SWIFT

Operated by: NASA

In service: 2004-

Swift is devoted to observing gamma-ray bursts (GRBs), huge explosions that often signal the collapse of massive stars and the creation of a black hole. In November 2015, Swift discovered its 1,000th GRB; such a milestone led NASA to report that the spacecraft "remains in great shape" after 11 years' service.

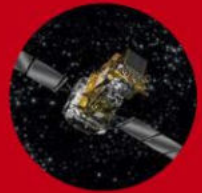


INTEGRAL

Operated by: European Space Agency

In service: 2002

Like Swift, INTEGRAL (aka INTERNATIONAL Gamma-Ray Astrophysics Laboratory) was charged with observing gamma rays. Originally a two-year mission, the spacecraft's fuel supply is such that it should still be in service beyond 2020.



XMM-NEWTON

Operated by: European Space Agency

In service: 1999-

The biggest-ever European-built scientific satellite observed much more than any existing X-ray satellite when it was launched at the tail end of the last millennium. Initially planned as a two-year mission to undertake various observations, the XMM-Newton (XMM stands for X-ray Multi-Mirror Mission) continues its work more than 16 years after its launch.



STEREO

Operated by: NASA

In service: 2006-

As the name suggests, STEREO is a mission involving two near-identical spacecraft. The orbit of one is ahead of Earth, while the orbit of the other is behind. Their main purpose is to record stereoscopic images of the Sun, photographing parts invisible from Earth.



JAMES WEBB SPACE TELESCOPE

Operated by: NASA

In service: 2018-tbc

The planned successor to Hubble, this \$8.8bn spacecraft will orbit Earth at a distance of 930,000 miles while its infra-red instruments observe light from the early universe. Named after influential Apollo administrator James E Webb, its launch is scheduled for October 2018.



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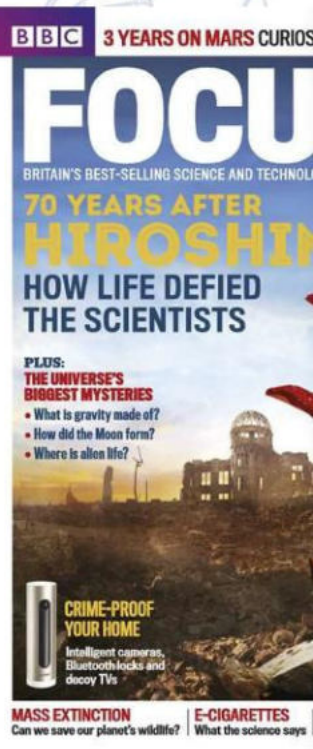
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Marcus splits his time between writing, broadcasting and performing stand-up comedy. He's the author of a number of books, among them *Quantum Theory Cannot Hurt You* and *We Need To Talk About Kelvin*



Catherine Offord

Catherine is a science writer who is currently studying for a PhD at Princeton University



Elizabeth Pearson

Elizabeth is the news editor of *BBC Sky at Night Magazine* and has a PhD in astrophysics from the University of Cardiff



Brian Clegg

Brian is the author of many science books, including *Science For Life: A Manual For Better Living* and *Gravity: Why What Goes Up Must Come Down*



Giles Sparrow

Giles is a science author whose books include *Hubble: Window On The Universe* and *The Cosmic Gallery*



Colin Stuart

Colin writes and broadcasts about science and is the author of *The Big Questions In Science* and *Physics In 100 Numbers*



John Gribbin

John is Visiting Fellow in Astronomy at the University of Sussex and the author of *In Search Of The Multiverse*



Govert Schilling

Govert is the author of *Atlas Of Astronomical Discoveries* and has an asteroid named after him – 10986 Govert



Robert Matthews

Robert combines a career as a science journalist and author with being Visiting Reader in Science at Aston University. His research has also won him an Ig Nobel Prize



Will Gater

Will is an astronomy journalist and broadcaster. His books include *The Cosmic Keyhole* and *The Practical Astronomer*



Amy Tyndall

Amy holds a PhD from the University of Manchester's Jodrell Bank Centre for Astrophysics and is currently "reaching for the stars in Chile"



Stuart Clark

Stuart is a Visiting Fellow of the University of Hertfordshire. His latest book is *The Day Without Yesterday*



Dave Jewitt

Dave is a professor at the University of California Los Angeles, as well as being the man who co-discovered the Kuiper Belt in 1992



Hazel Muir

Hazel studied astrophysics before becoming a science journalist. She is the author of *Eureka! Science's Greatest Thinkers And Their Key Breakthroughs*



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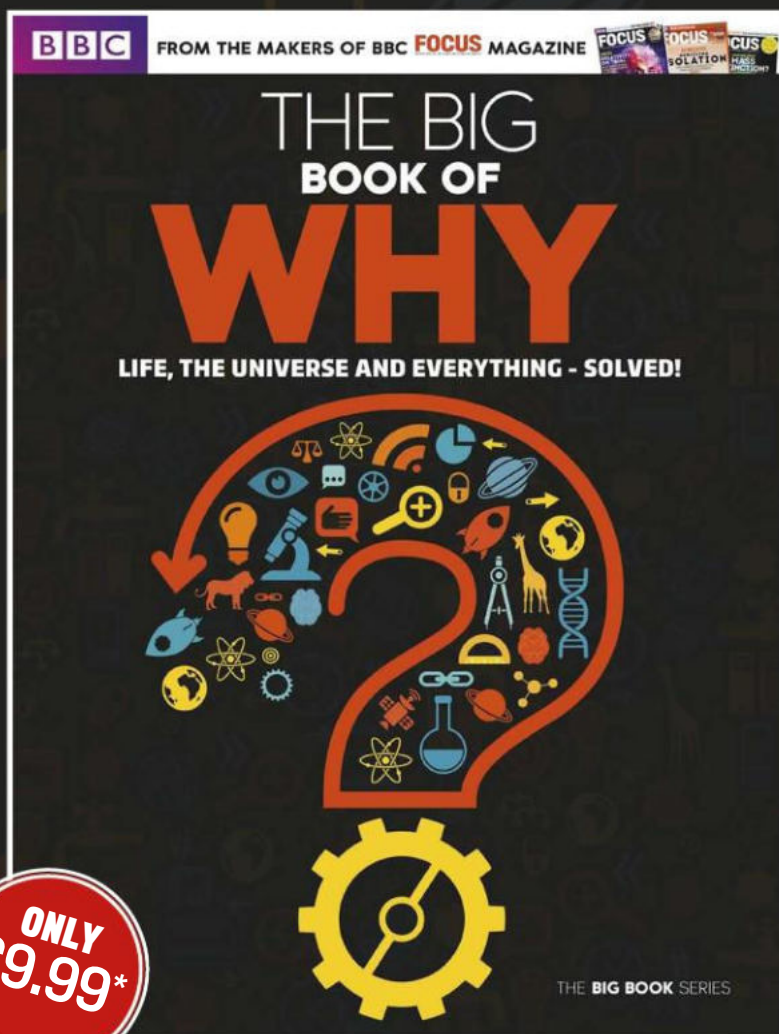
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